

DarkSide-50

Results with UAr

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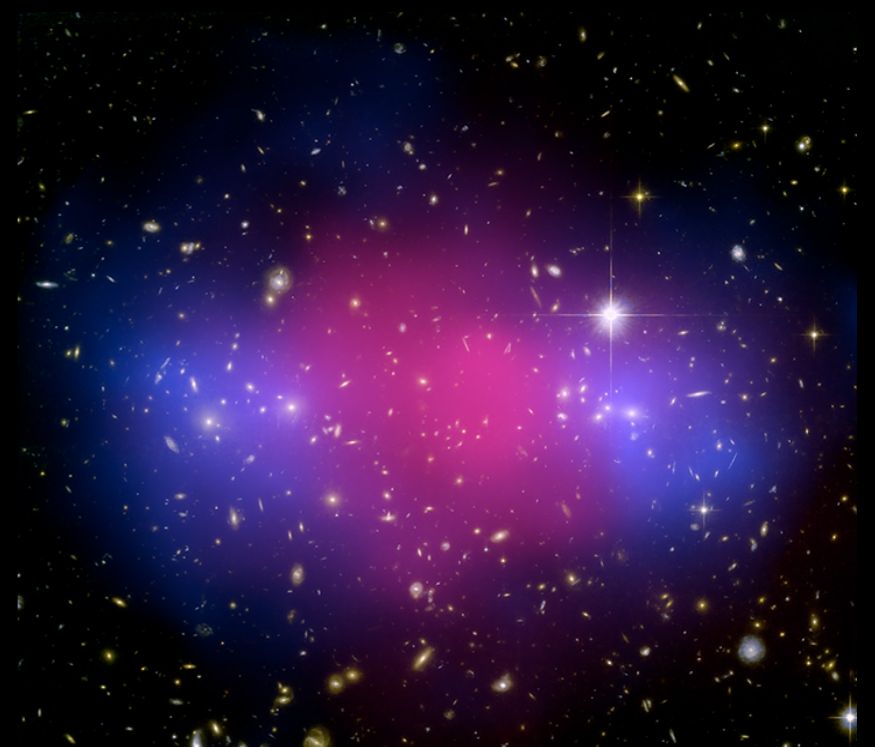
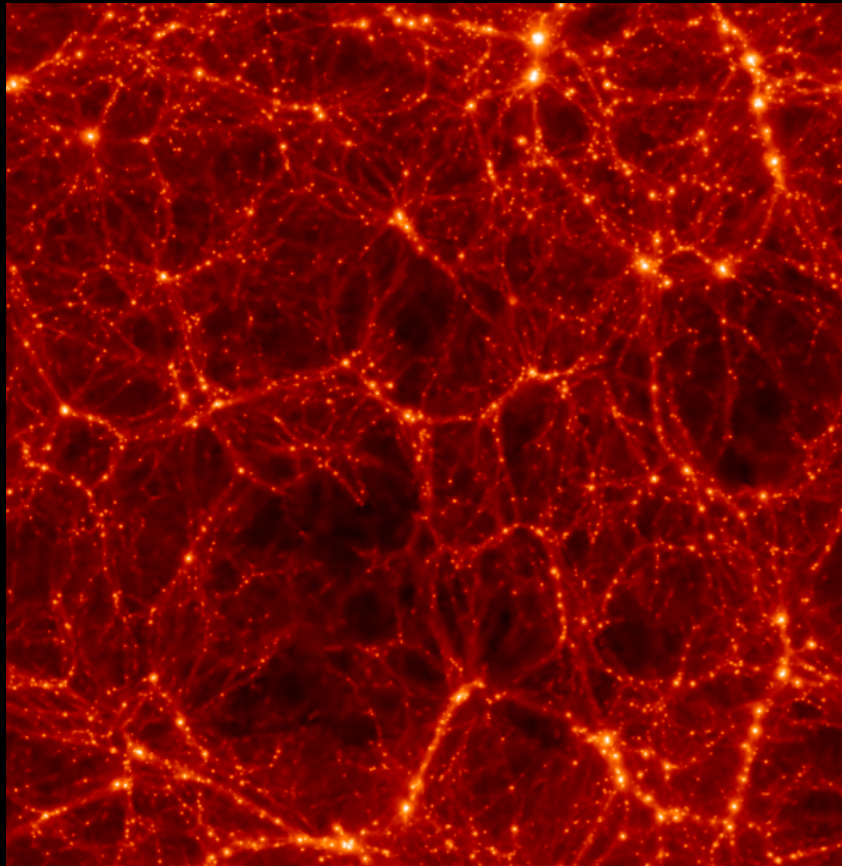
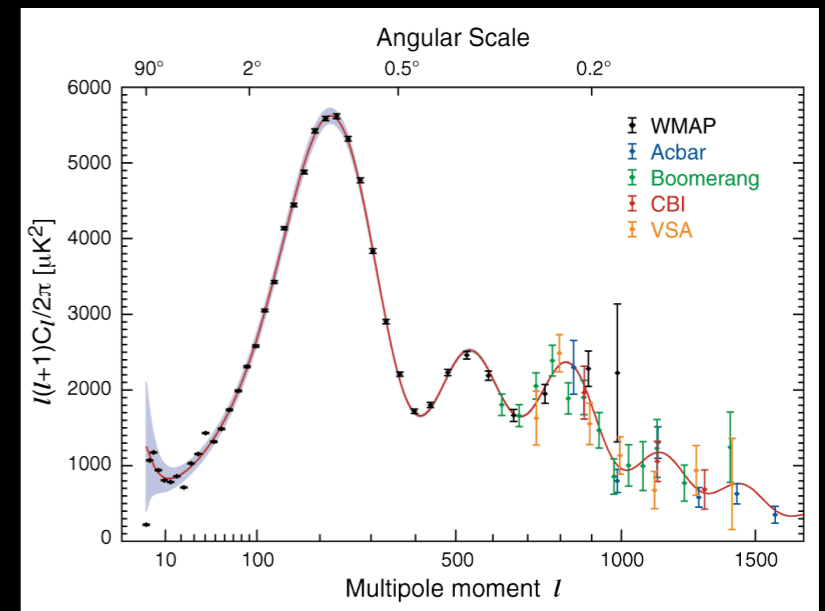
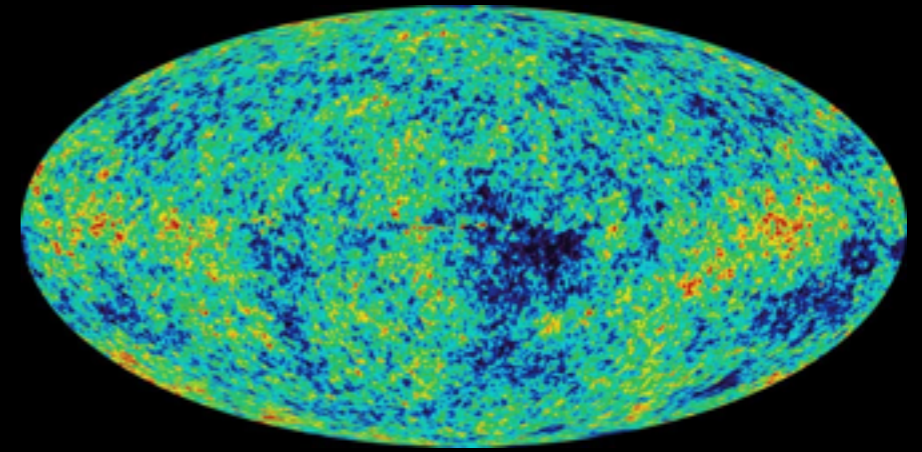
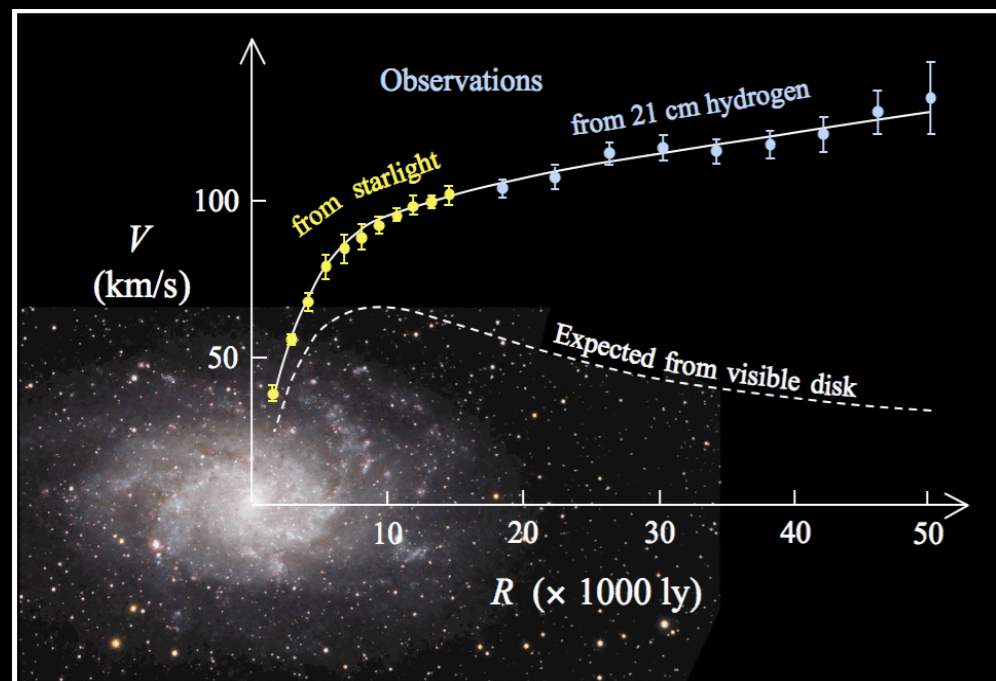
on behalf of the DarkSide Collaboration

23 Nov. 2015

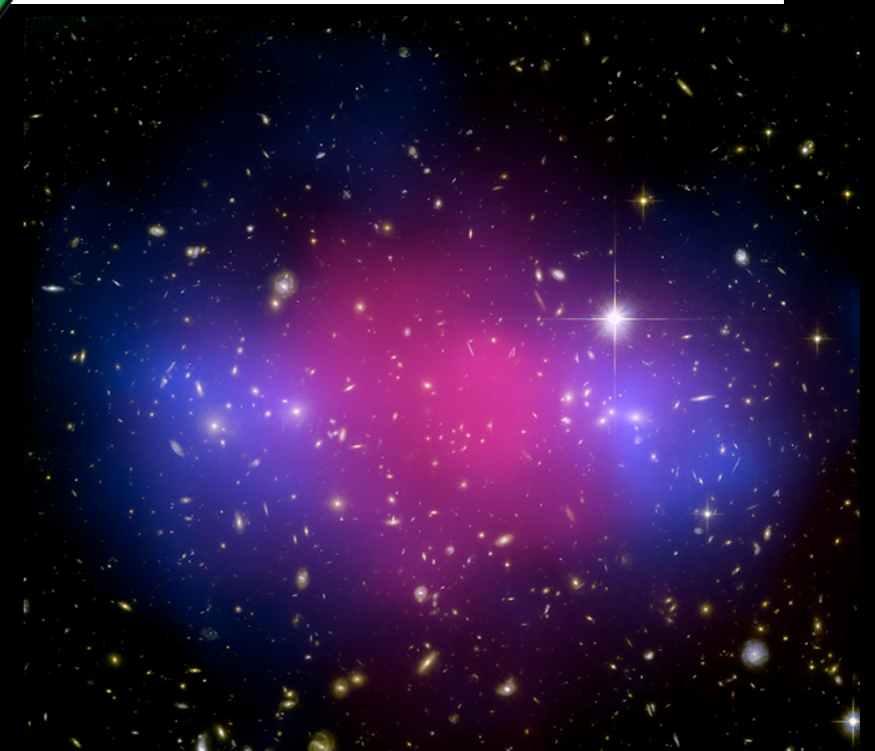
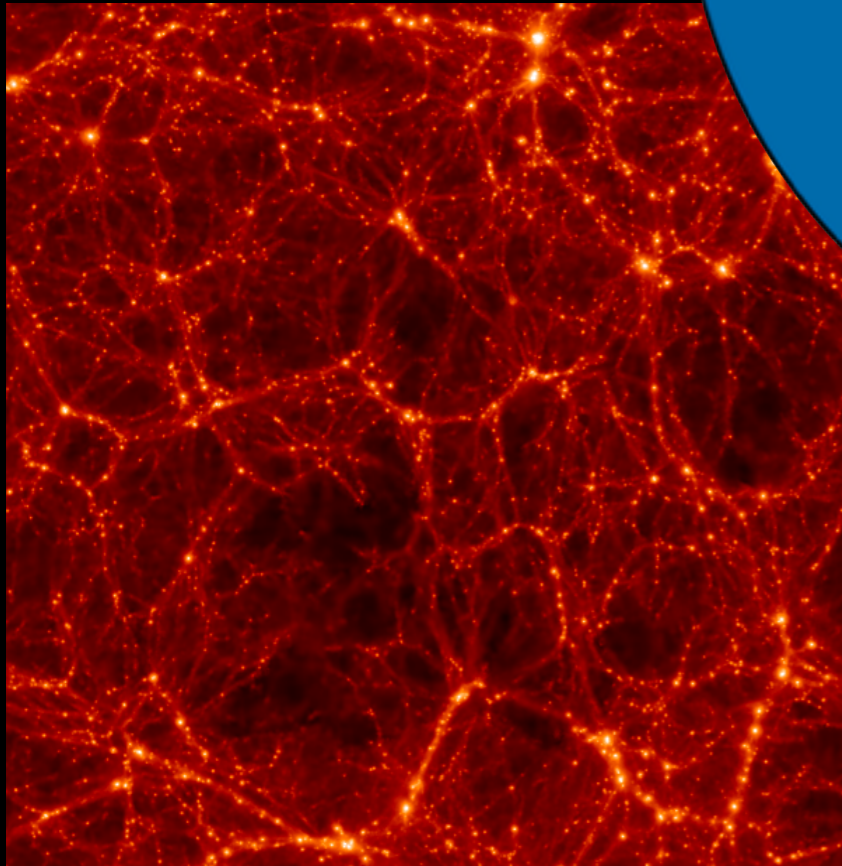
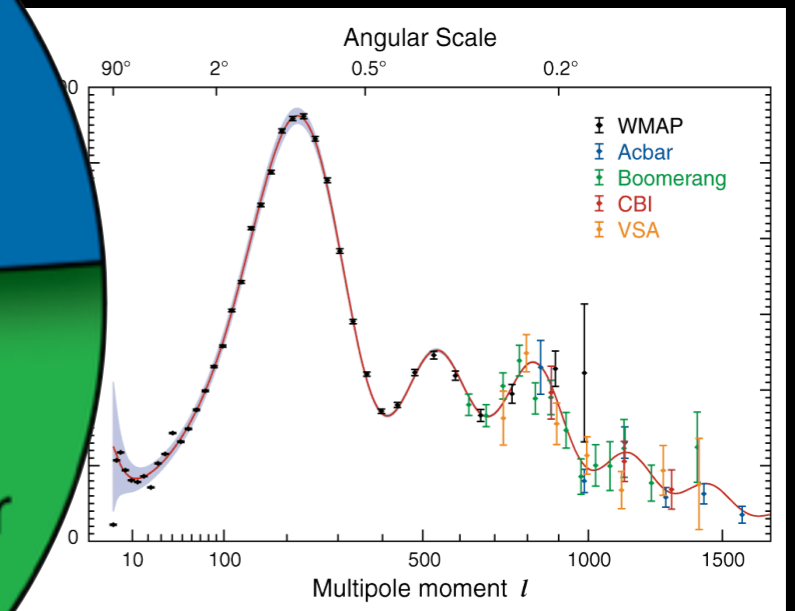
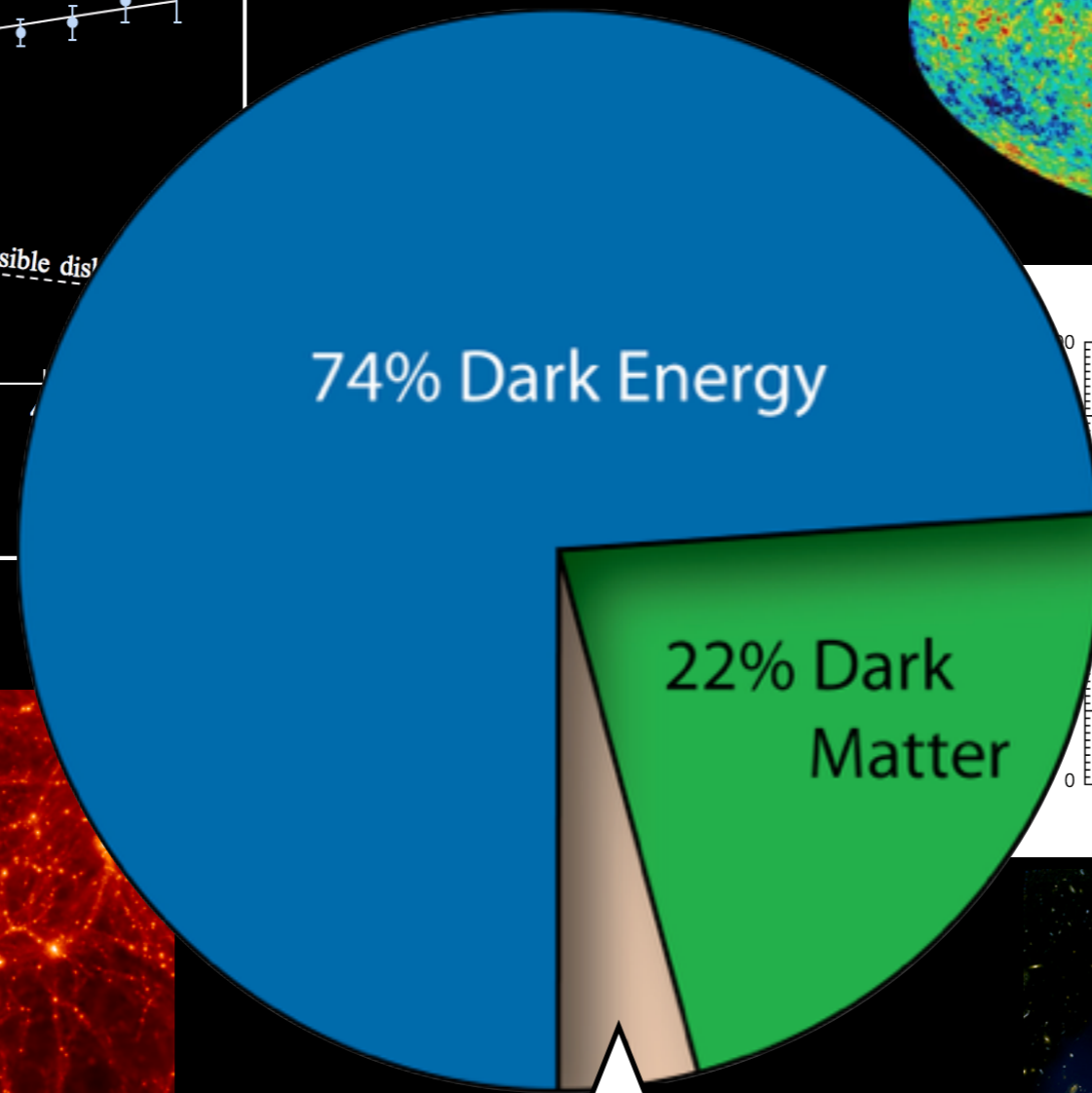
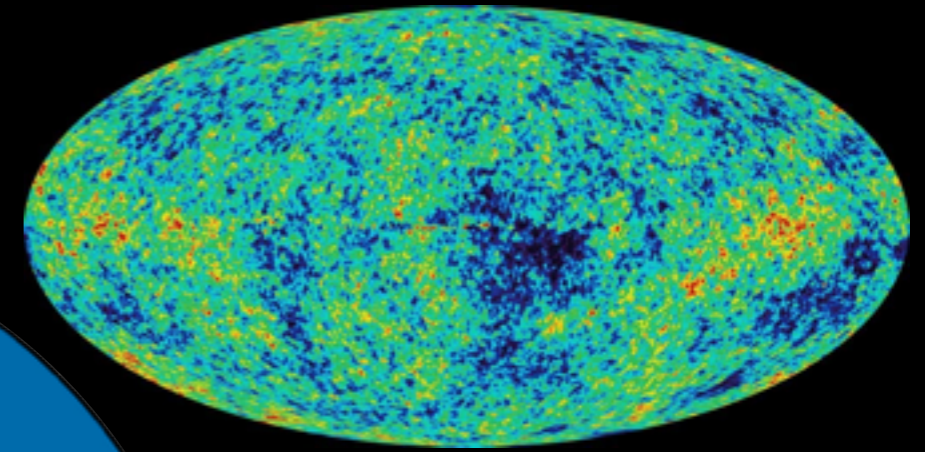
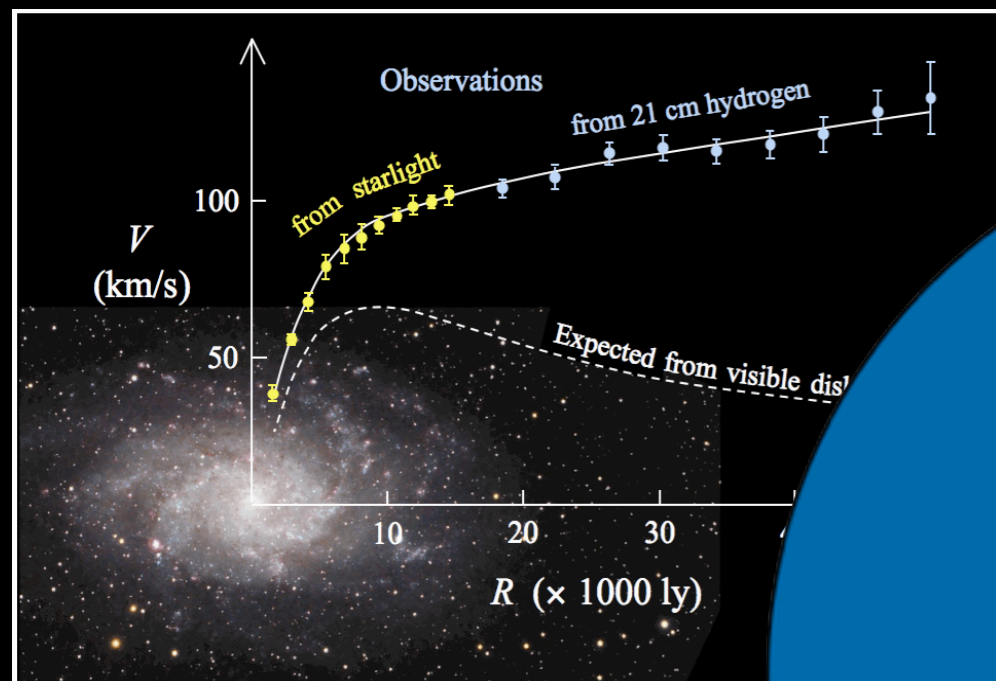
Outline

- Introduction to Direct Detection of Dark Matter
- DarkSide Program
- DarkSide-50
- Physics result with Atmospheric Argon (**AAr**)
- Physics result with Underground Argon (**UAr**)

Evidence for Dark Matter

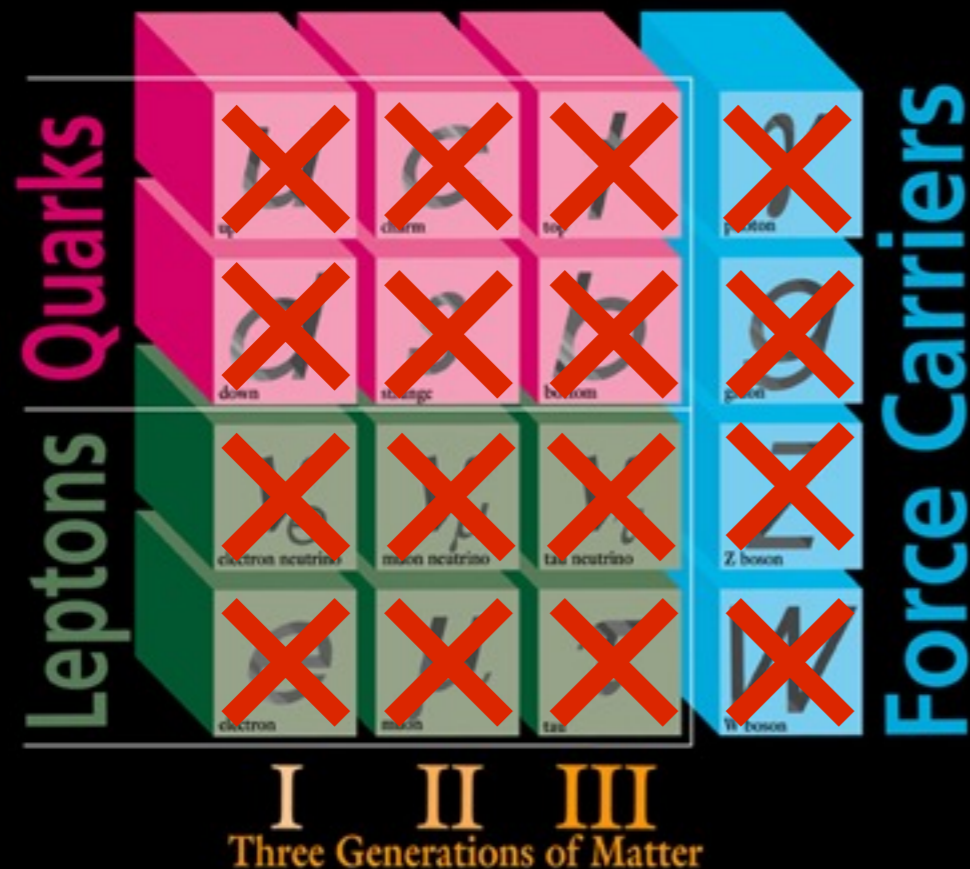


Evidence for Dark Matter



Dark Matter Properties

ELEMENTARY PARTICLES



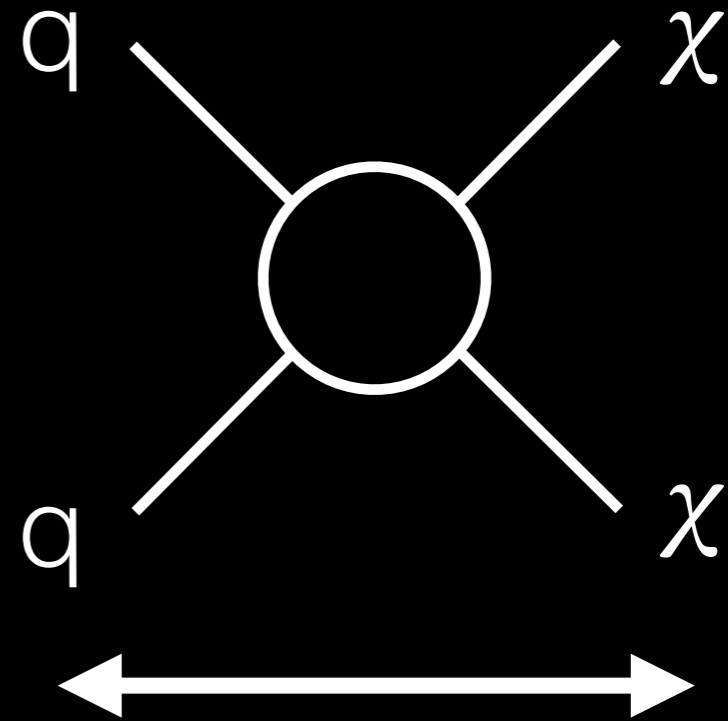
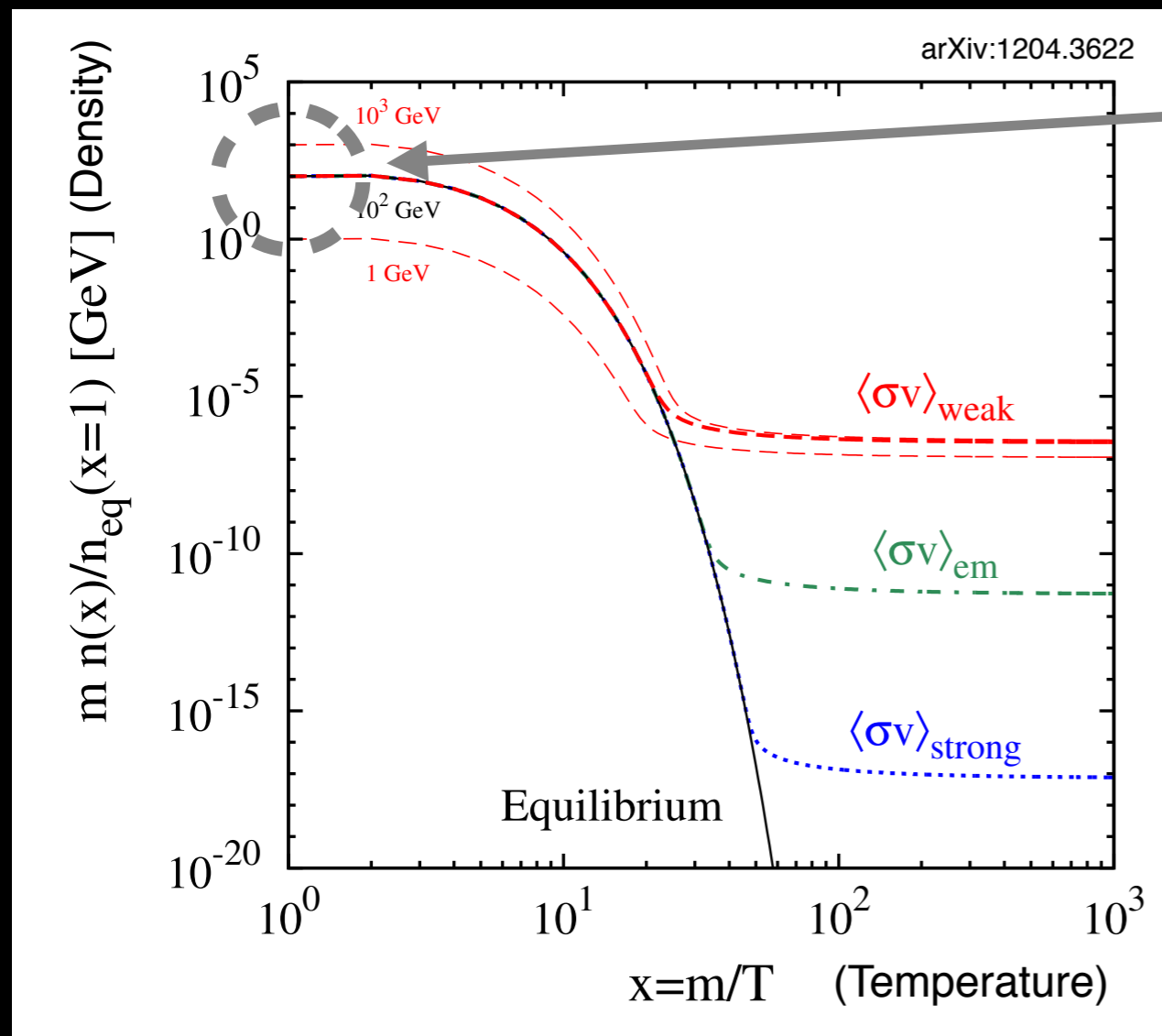
- Gravitationally interacting
- Stable particle
- Not Hot
- Not Baryon (Big Bang nucleosynthesis)

Beyond Standard Model!!

One of the most physics motivated candidates is Weak Interacting Massive Particles (**WIMP**).

Why WIMP?

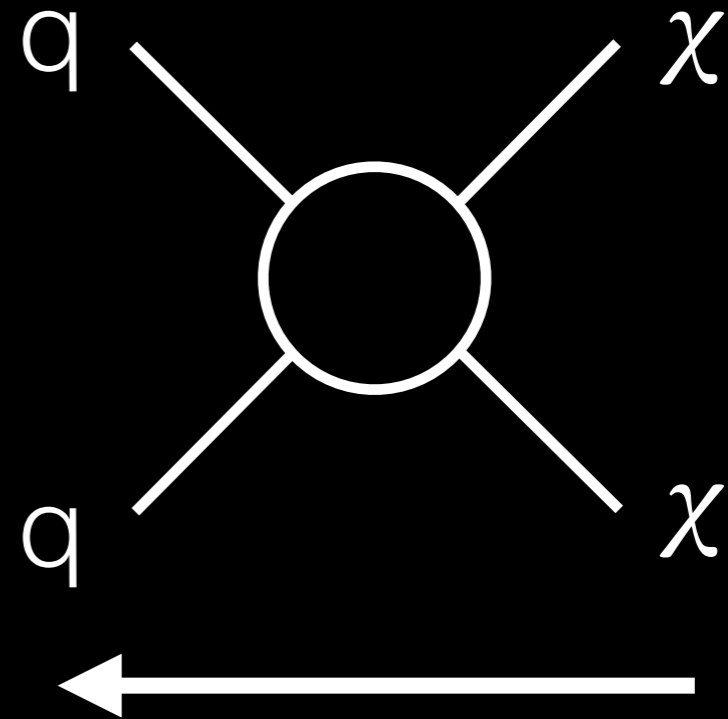
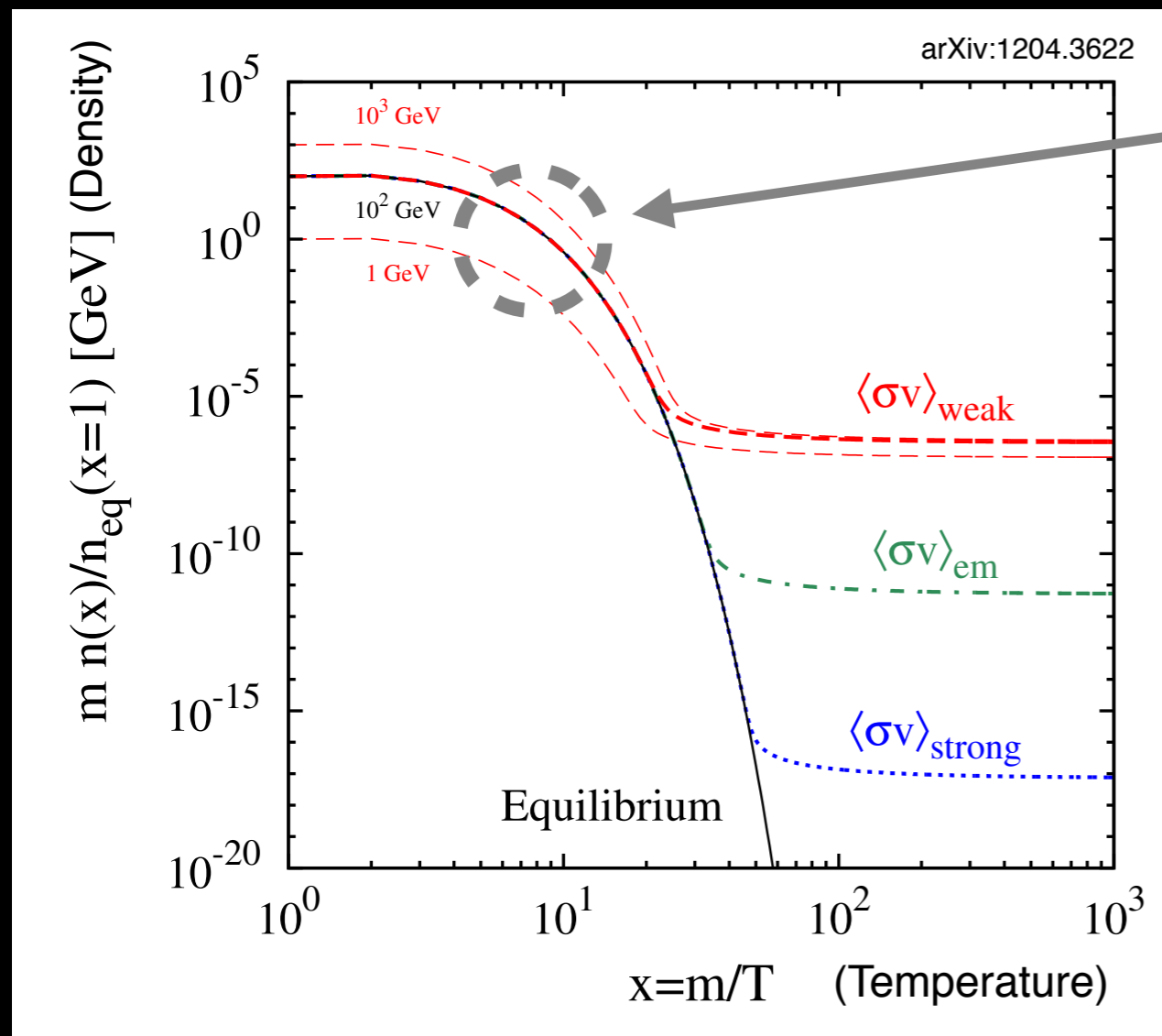
Thermal Relic (WIMP miracle)



When $T \gg m$, equilibrium

Time

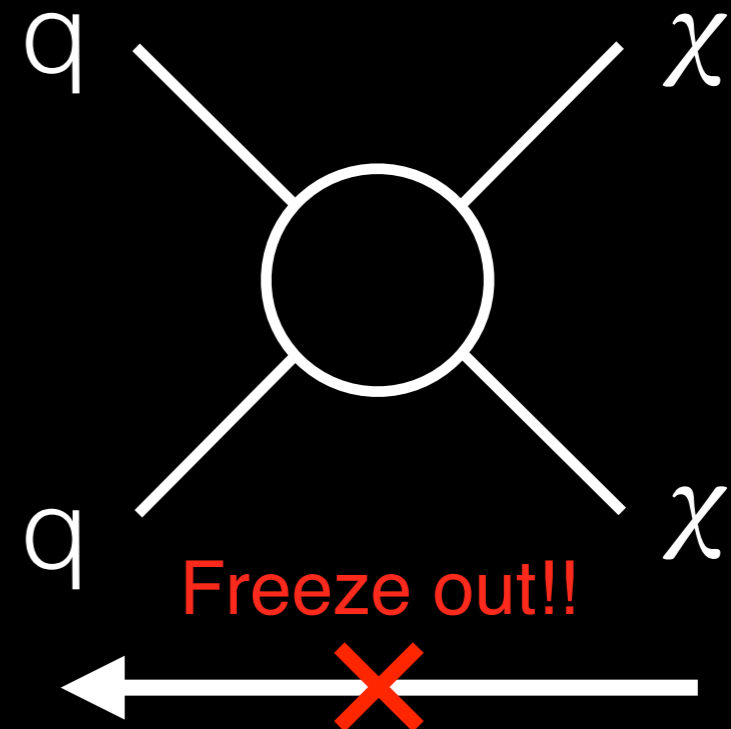
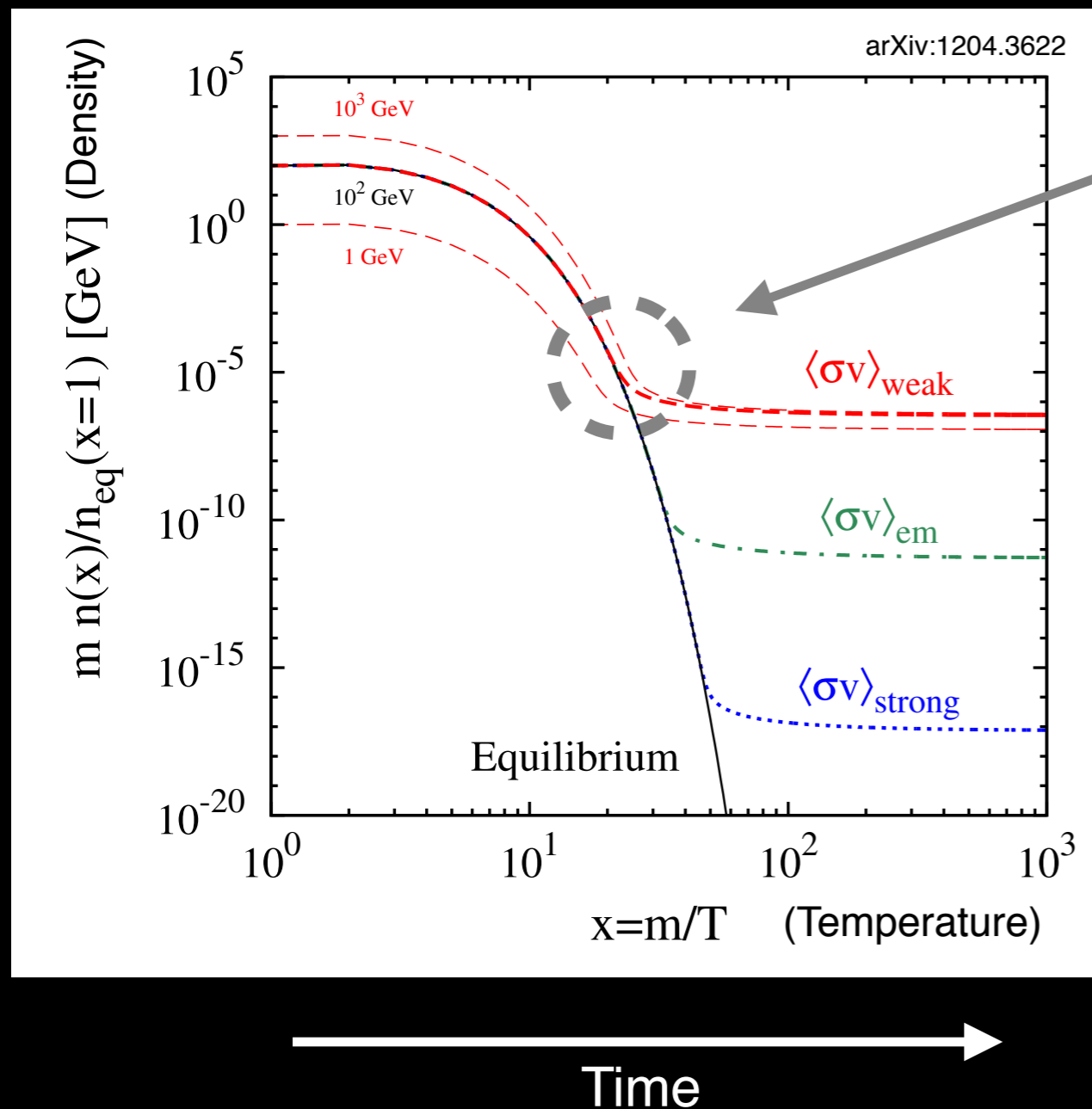
Thermal Relic



When $T < m$, χ decay exponentially.

Time →

Thermal Relic



When $\Gamma = H$, χ can not find each other.

$$\Gamma = n(x)\langle\sigma v\rangle \Rightarrow n_f(x) = H/\langle\sigma v\rangle$$

Weak-scale cross section reproduces the relic abundance of DM expected from Λ CDM.

New Physics at Electroweak scale?

- **Higgs Hierarchy problem** also indicates new physics at electroweak scale for Higgs to be at 125 GeV/c², otherwise Higgs would be much heavier ($\sim 10^{18}$ GeV/c², the Planck mass).
- **New physics at weak scale** can solve both problems.

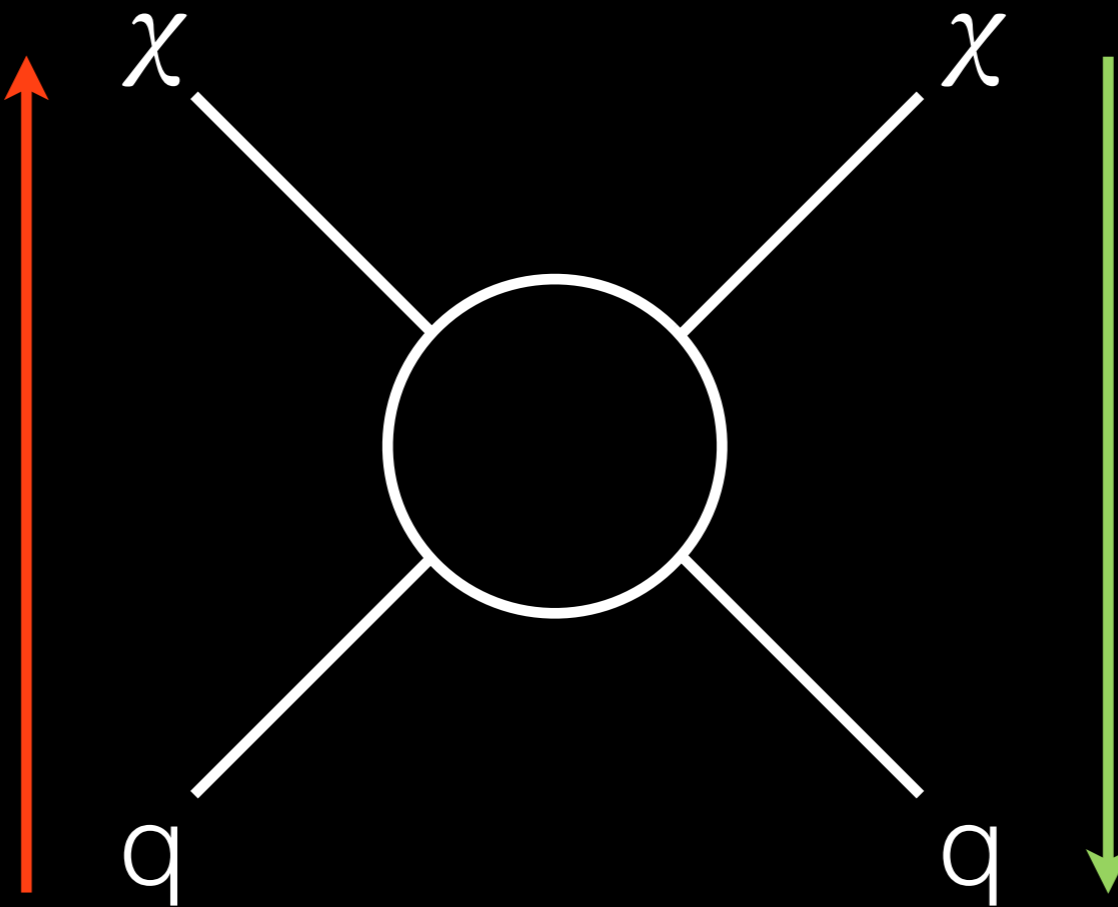
Detecting WIMPs

Production

Annihilation



Indirect
Detection



Colliders

Scatt

ect
ction



Direct Detection Rates

$$R \text{ (events/kg/yr)} = \langle \Phi_{\chi} \cdot \sigma_{\chi-N} \rangle \cdot n$$

Φ_{χ}

Flux of WIMPS

$\sigma_{\chi-N}$

WIMP-Nucleus Scattering Cross Section

n

Target Nuclei / kg

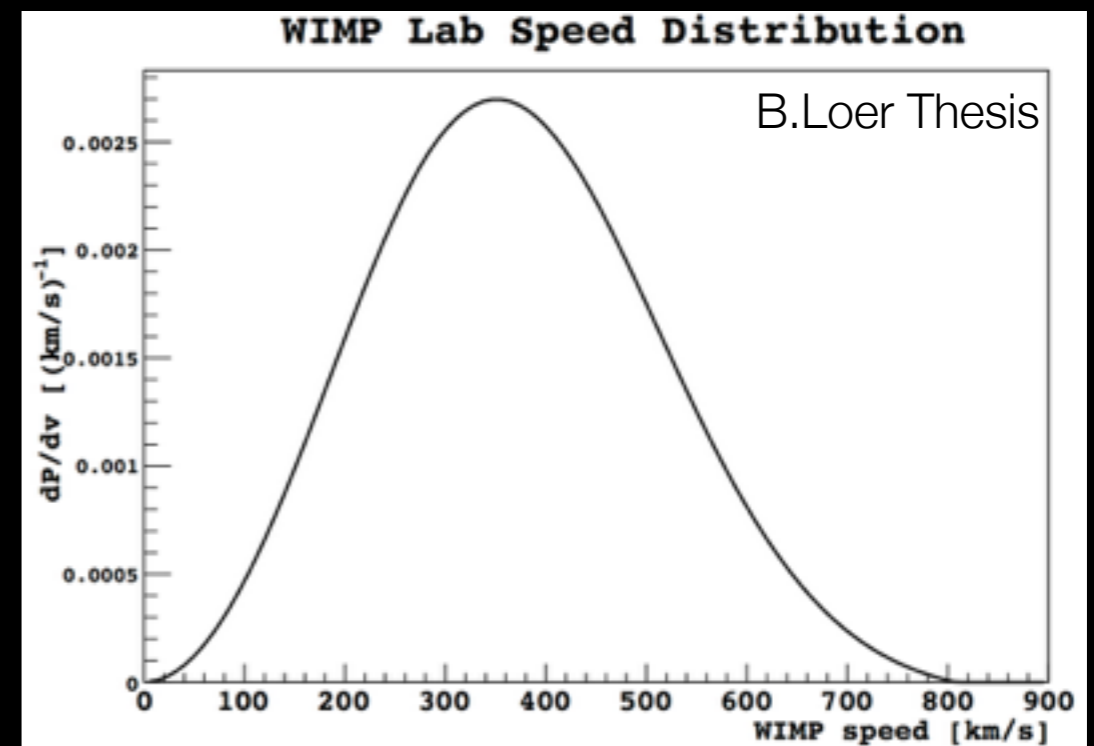
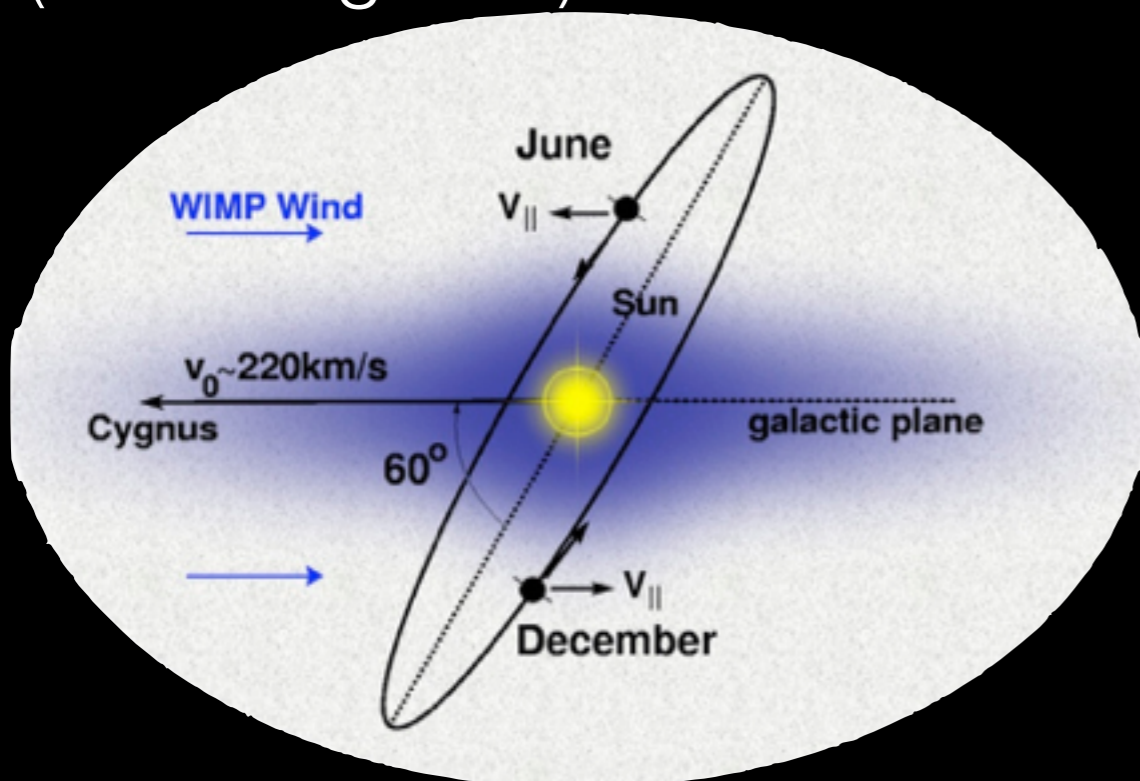
$$R \text{ (events/kg/yr)} = \langle \Phi \cdot \sigma \rangle \cdot n$$

Surrounded by a Dark Matter Halo

$$\Phi(v) = \frac{\rho_\chi}{m_\chi} v_\chi f(v_\chi, t)$$

Local density
 $\sim 0.3 \text{ GeV/cm}^3$
 $(5 \times 10^{-25} \text{ g/cm}^3)$

Maxwellian Velocity Distribution
 Local speed $\sim 220 \text{ km/s}$
 Escape Velocity $\sim 500 - 600 \text{ km/s}$



$$R \text{ (events/kg/yr)} = \langle \Phi \cdot \sigma \rangle \cdot n$$

WIMP - Nucleus SI Scattering Cross-Section

$$\sigma(v_\chi) \propto \frac{M_N}{\mu_n^2 v_\chi^2} \cdot \sigma_n \cdot A^2 \cdot F^2(q)$$

WIMP-Nucleon
Cross-Section

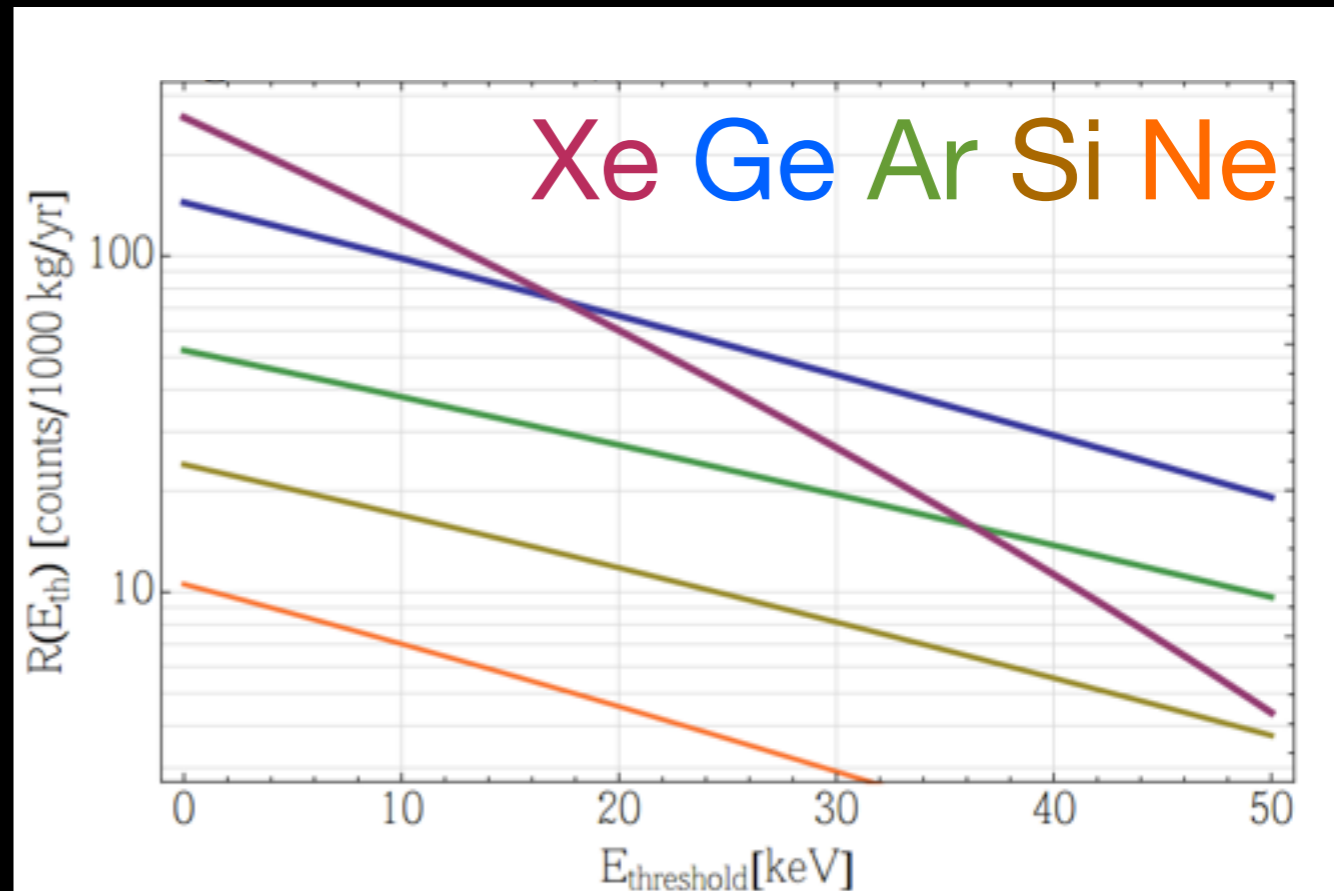
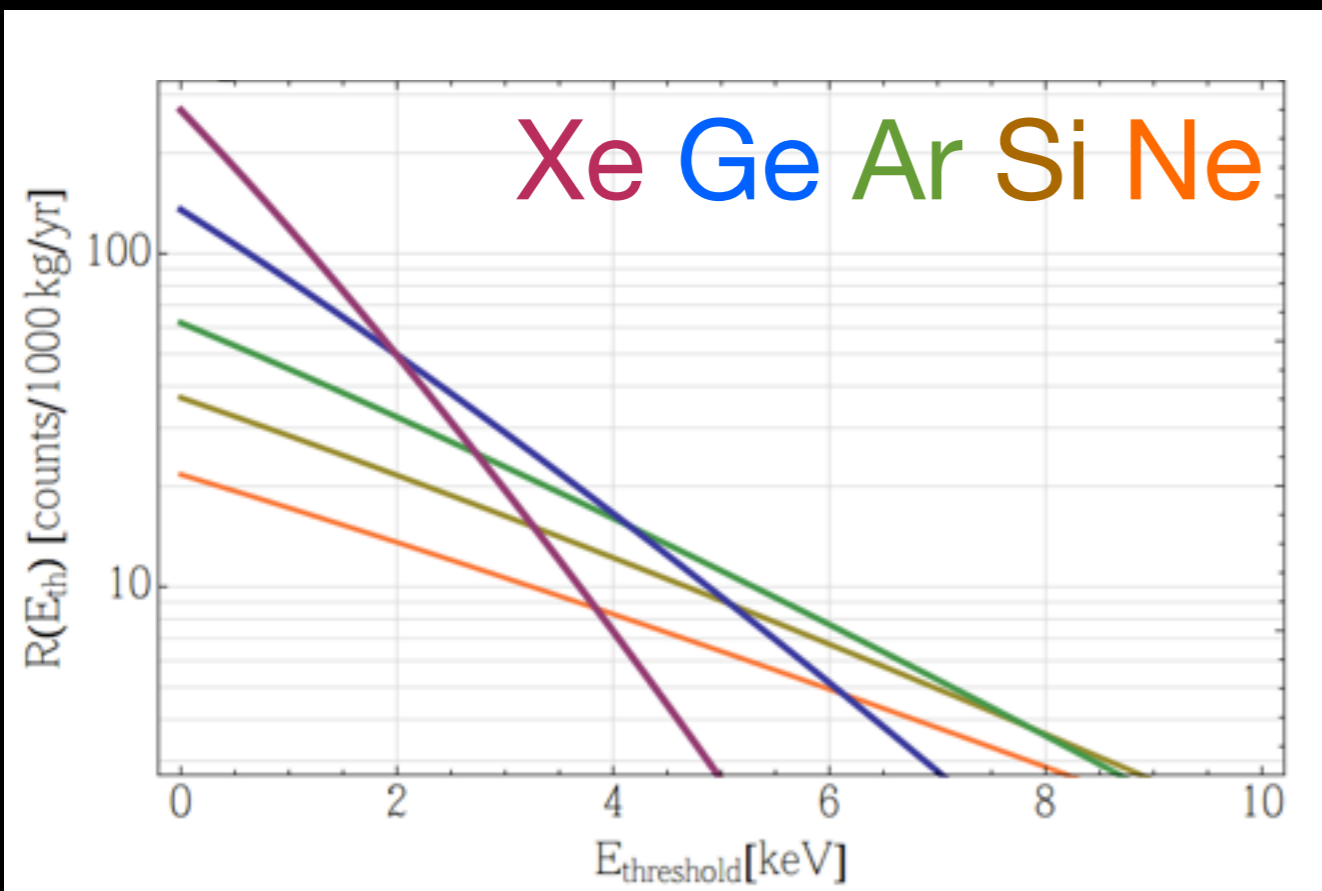
Mass number of nucleus
(assumes same interaction
for neutrons and protons)

Nuclear Form Factor
Correction for
decoherence at
non-zero
momentum transfer

Interaction Rates

m_χ : 10 GeV, $\sigma_{\chi-n}$: 10^{-45} cm²

m_χ : 100 GeV, $\sigma_{\chi-n}$: 10^{-45} cm²



arXiv:1310.8327v2 [hep-ex]

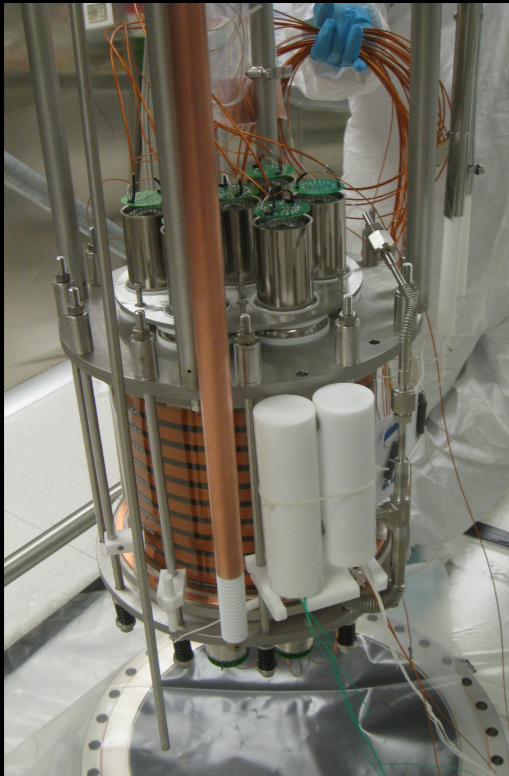
Total Interaction Rate for Ar $\sim 10^{-4}$ evt/kg/day
 Rock Natural Radioactivity $\sim 10^7$ evt/kg/day

DarkSide Program

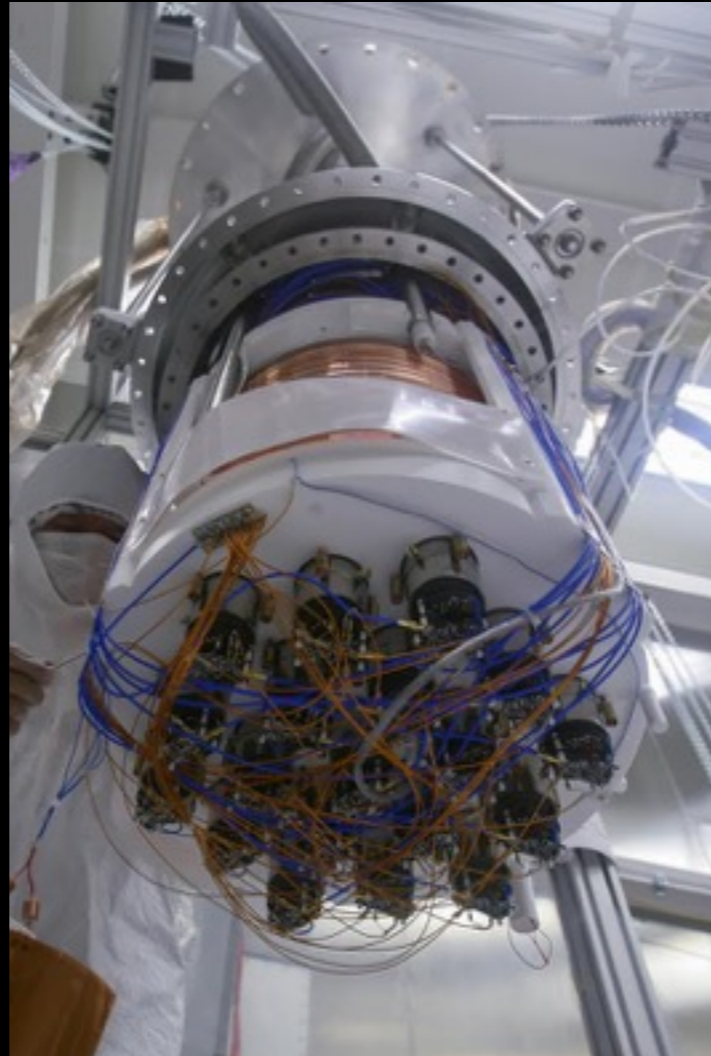
- **Direct detection** search for WIMP dark matter
- Based on a **two-phase argon** time projection chamber (**TPC**)
- Design philosophy based on having very low background levels that can be further reduced through **active suppression**, for **background-free** operation from backgrounds (both from neutrons and β/γ 's)

DarkSide Program

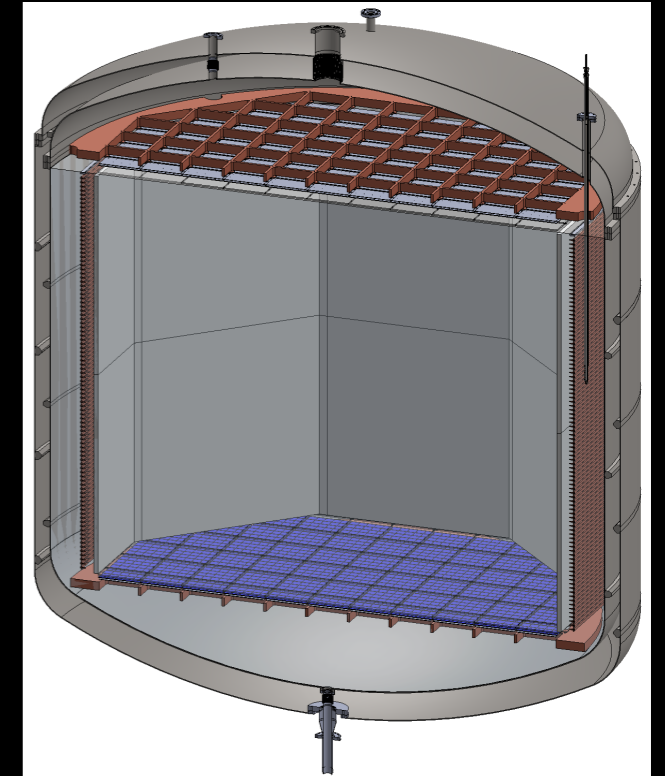
Multi-stage program at Gran Sasso National Laboratory in Italy



DarkSide 10
Prototype detector



DarkSide 50
First physics detector
Commissioned Oct.2013



DarkSide-20k
30 tonne (20 tonne
fiducial depleted argon
detector proposed to
LNGS for operations
within **2020**)

+ multiple smaller test setups and prototypes

Gran Sasso

3800 m w. e.

Deep underground location at LNGS, Italy.



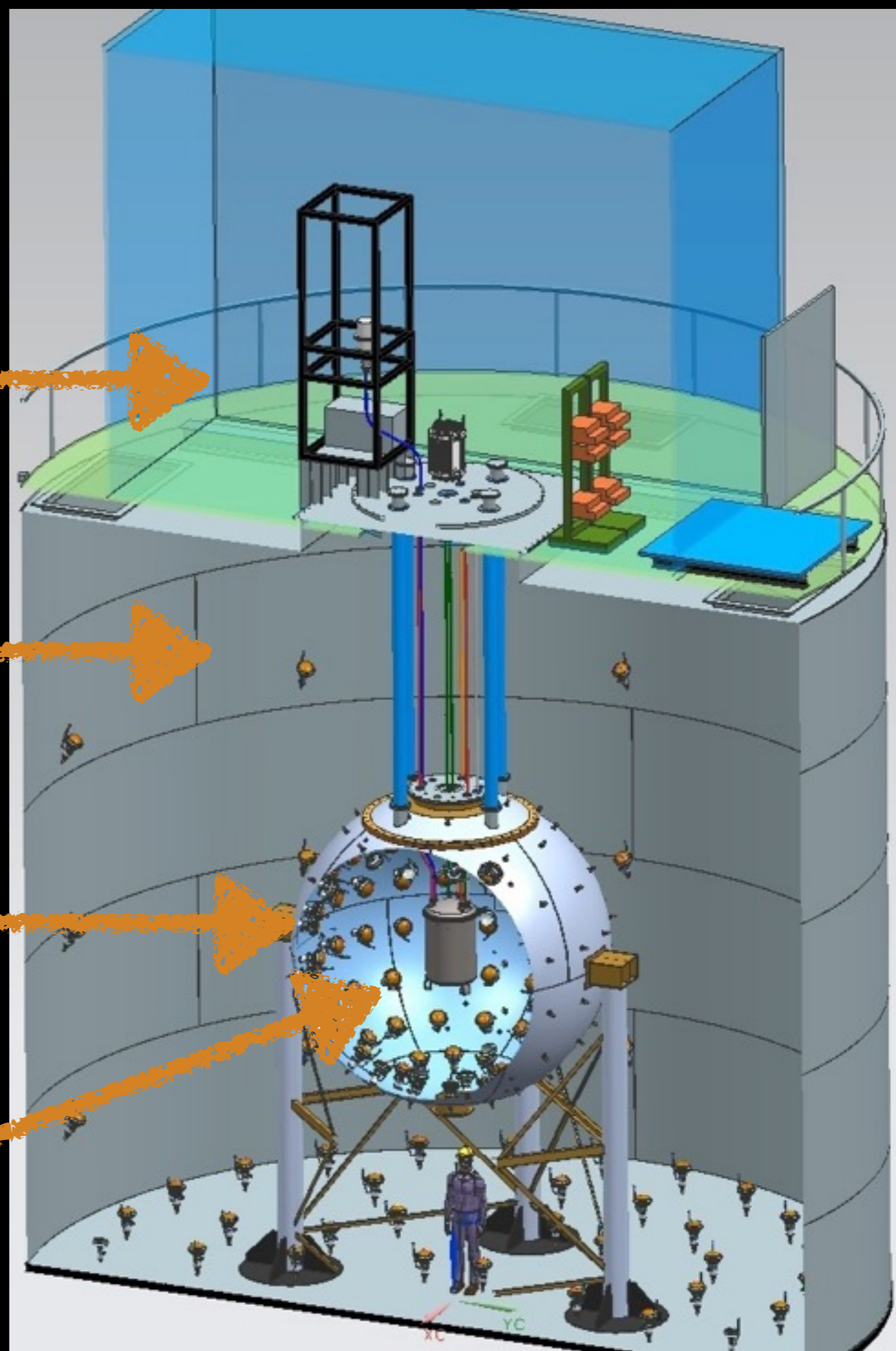
DarkSide 50

Radon-free Assembly
Clean Room

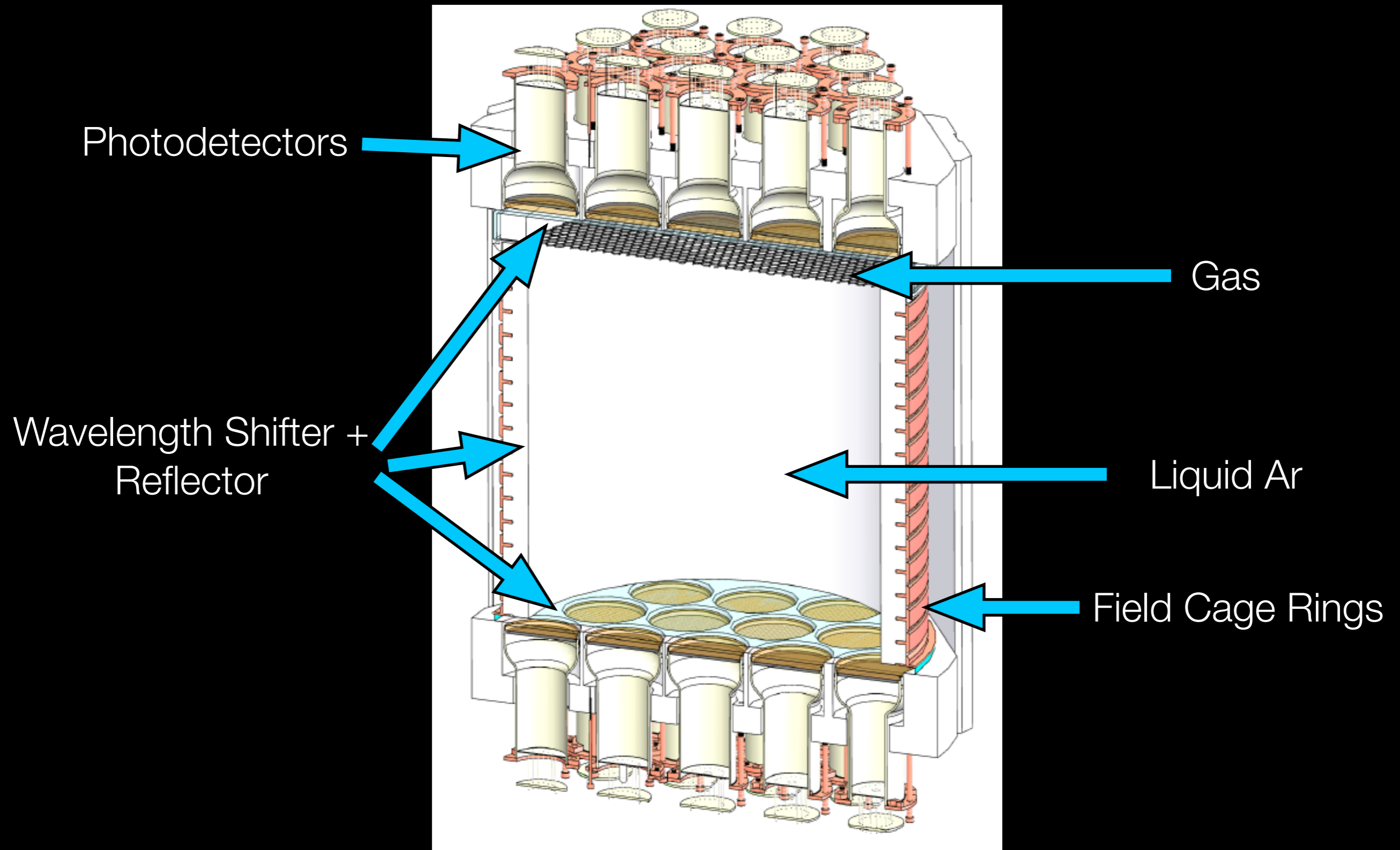
1,000-tonne Water-based
Cherenkov **Cosmic Ray Veto**

30-tonne Liquid Scintillator
Neutron and γ 's Veto

Inner detector **TPC**

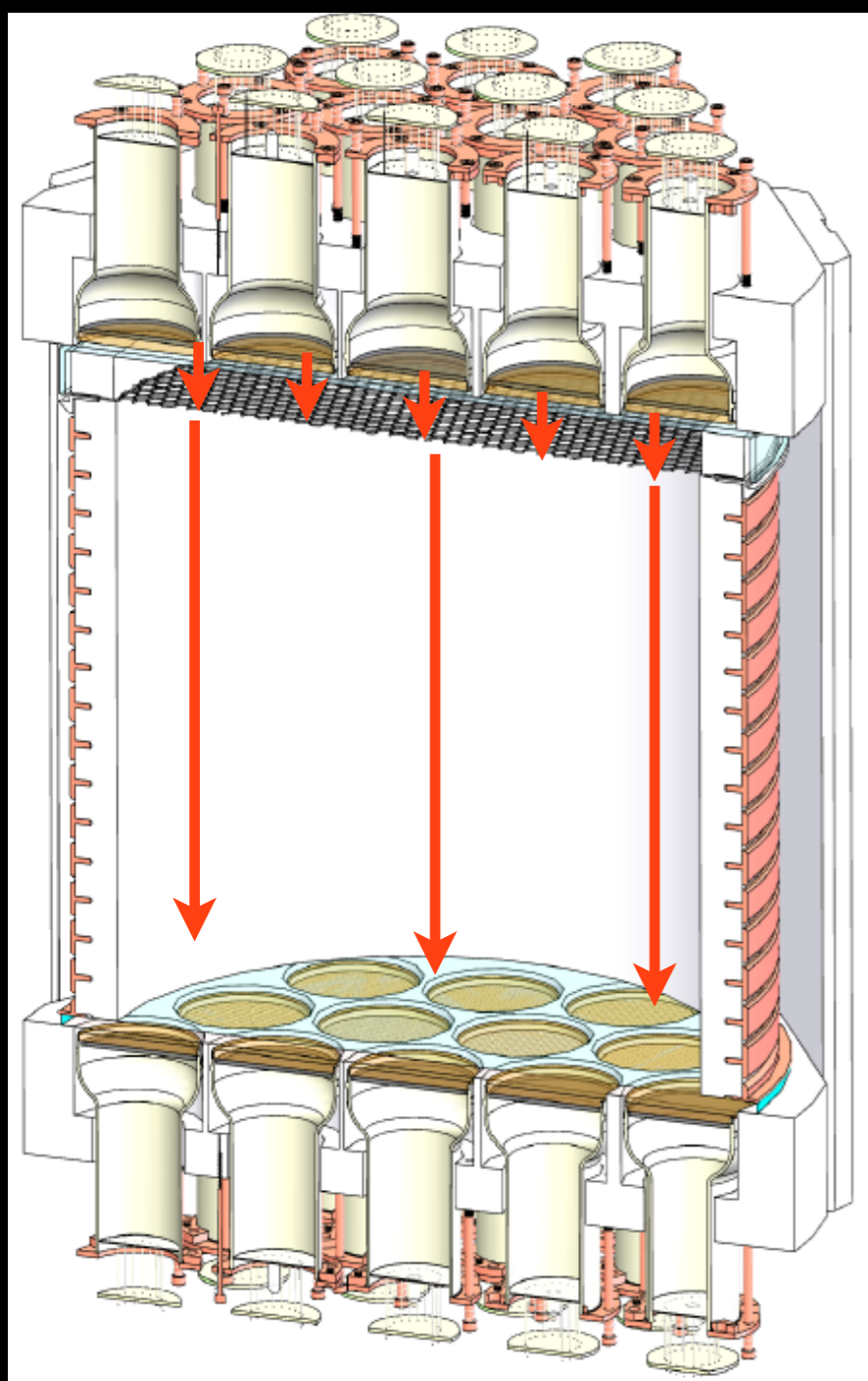


Two Phase Argon TPC



Drift Field

DS50 has been operating at a drift field of 200 V/cm
and an extraction field of 2.8 kV/cm



Anode: 0 V

$E_{\text{gas}} : 4200 \text{ V/cm}$

$E_{\text{ext}} : 2800 \text{ V/cm}$

Grid: -5600 kV

$E_{\text{drift}} : 200 \text{ V/cm}$

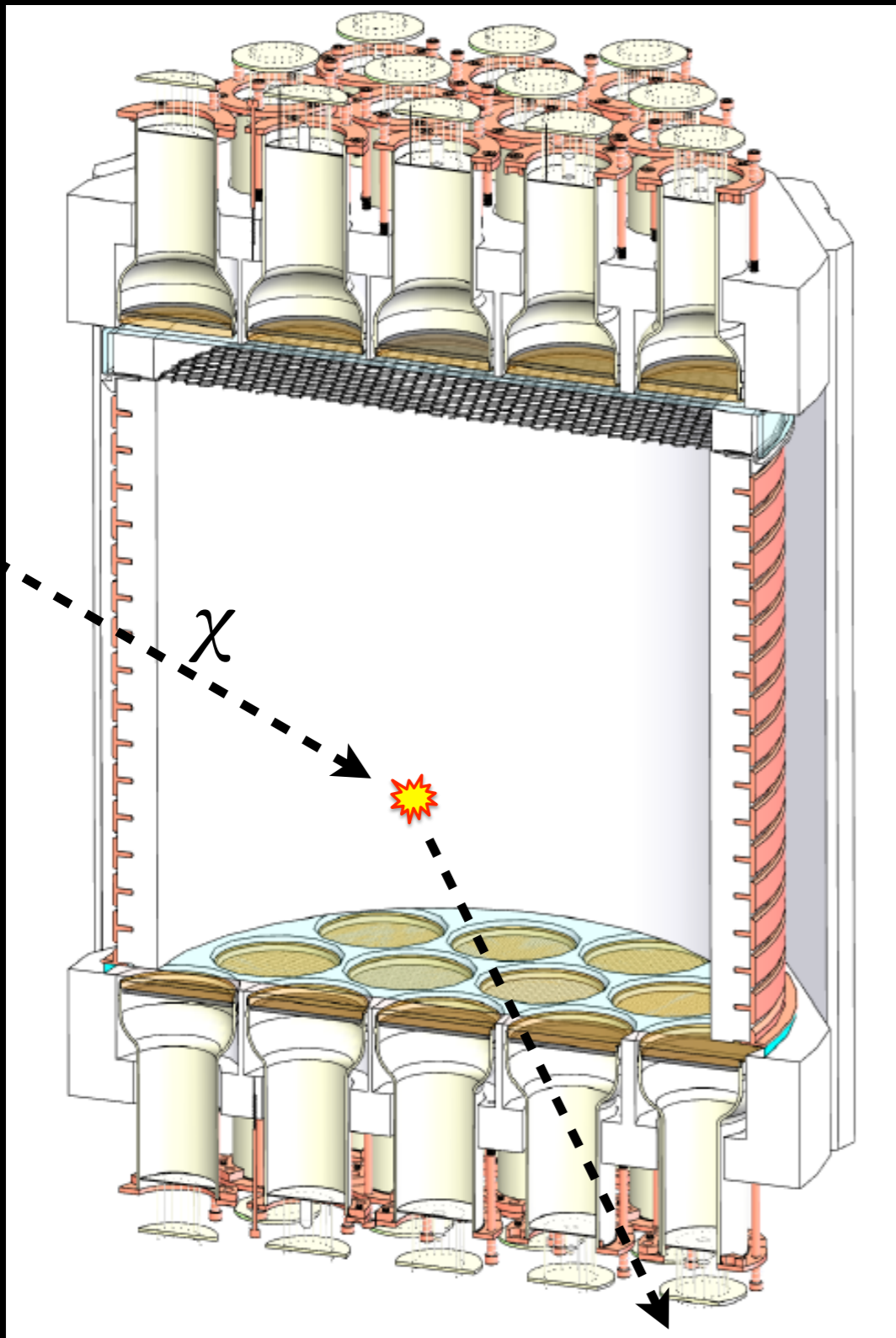
Cathode: -12700 V

Stable operation for two
years at -12700 V

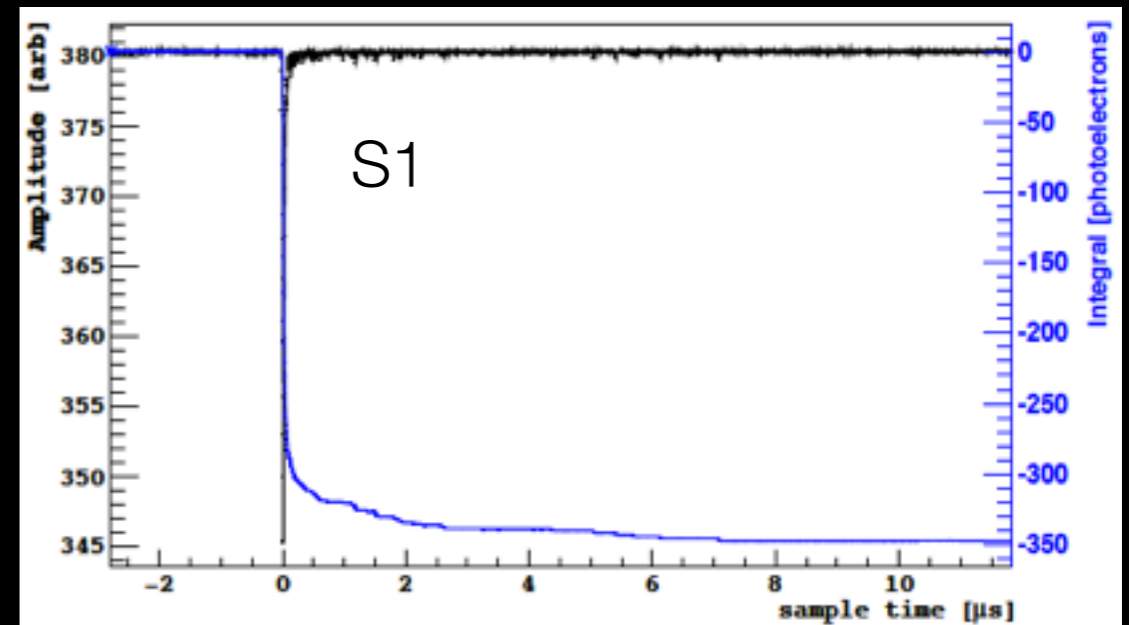
Max Drift Time $\sim 370 \text{ us}$

Electron Drift Lifetime $> 5\text{ms}$

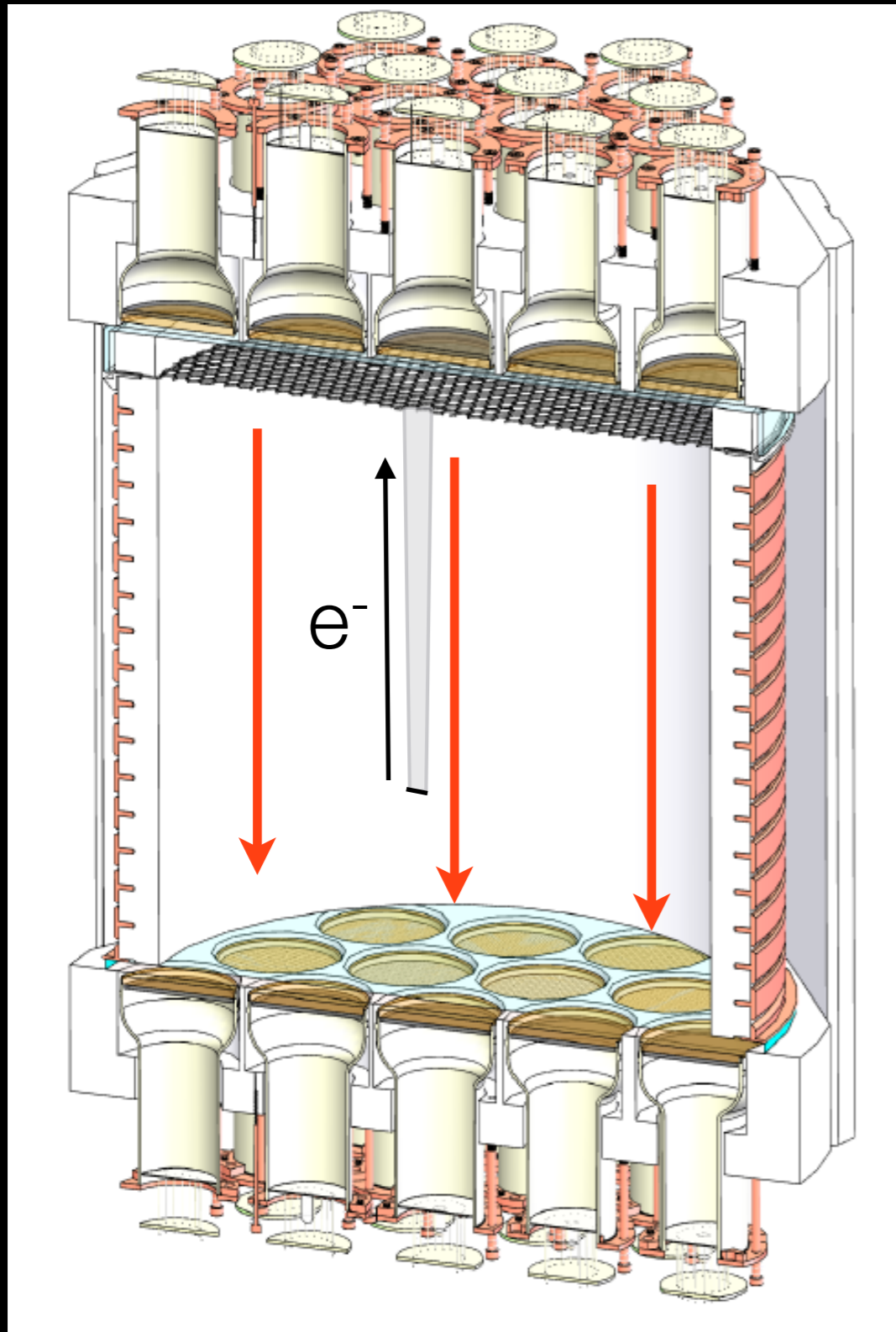
Two Phase Argon TPC



Nuclear Recoil excites and ionizes the liquid argon, producing scintillation light (S1) that is detected by the photomultipliers



Detecting WIMPs

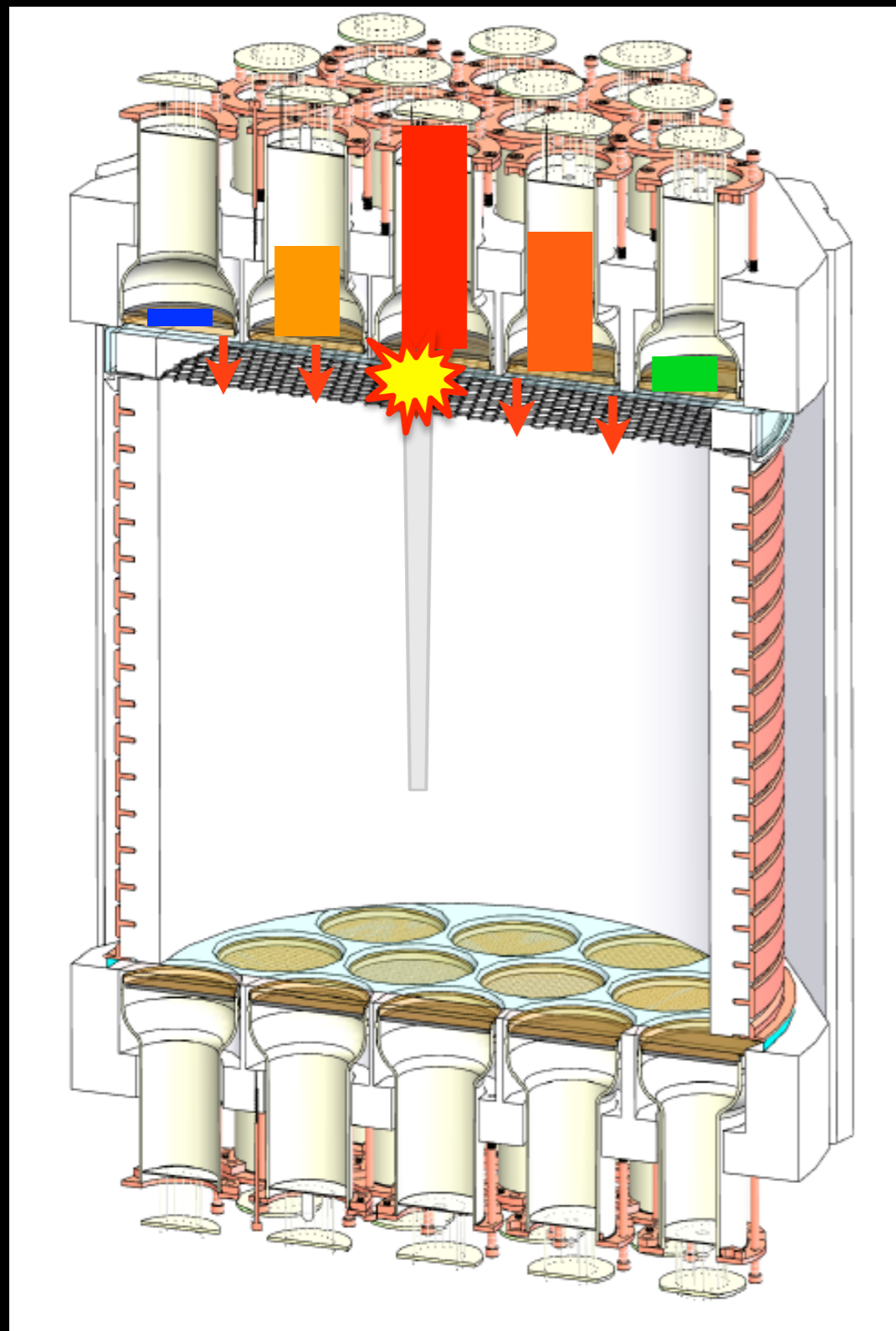


The ionized electrons that survive recombination are drifted towards the liquid-gas interface by the electric field.

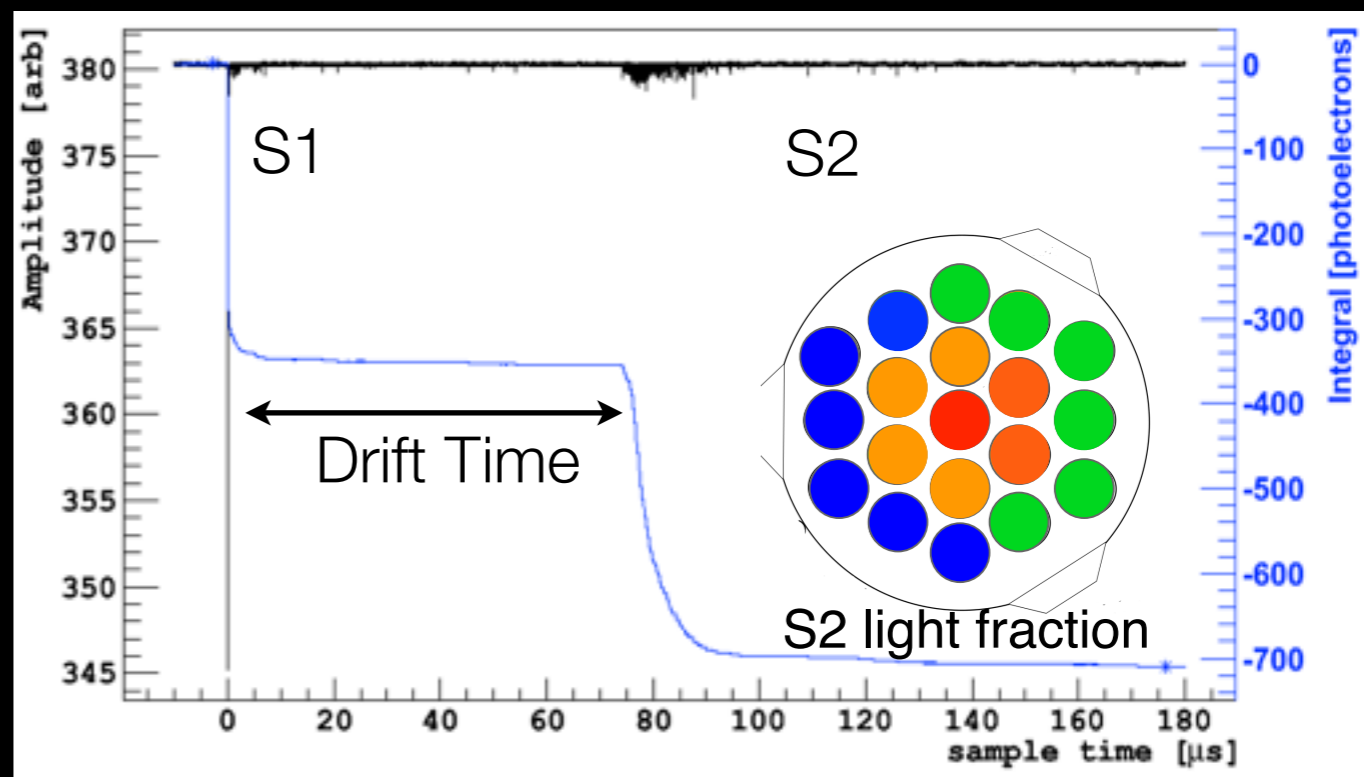
Electron drift lifetime > 5 ms,
compared to max. drift time of ~ 375 μ s

Electron drift speed = 0.93 ± 0.01 mm/ μ s

Detecting WIMPs



The electrons are extracted into the gas region, where they induce electroluminescence (S2)



- The time between the S1 and S2 signals gives the vertical position.
- x-y position of events are reconstructed from fraction of S2 in each PMT.

Backgrounds

ELECTRON RECOILS

^{39}Ar

$\sim 9 \times 10^4 \text{ evt/kg/day}$

γ

$\sim 1 \times 10^2 \text{ evt/kg/day}$

NUCLEAR RECOILS

μ

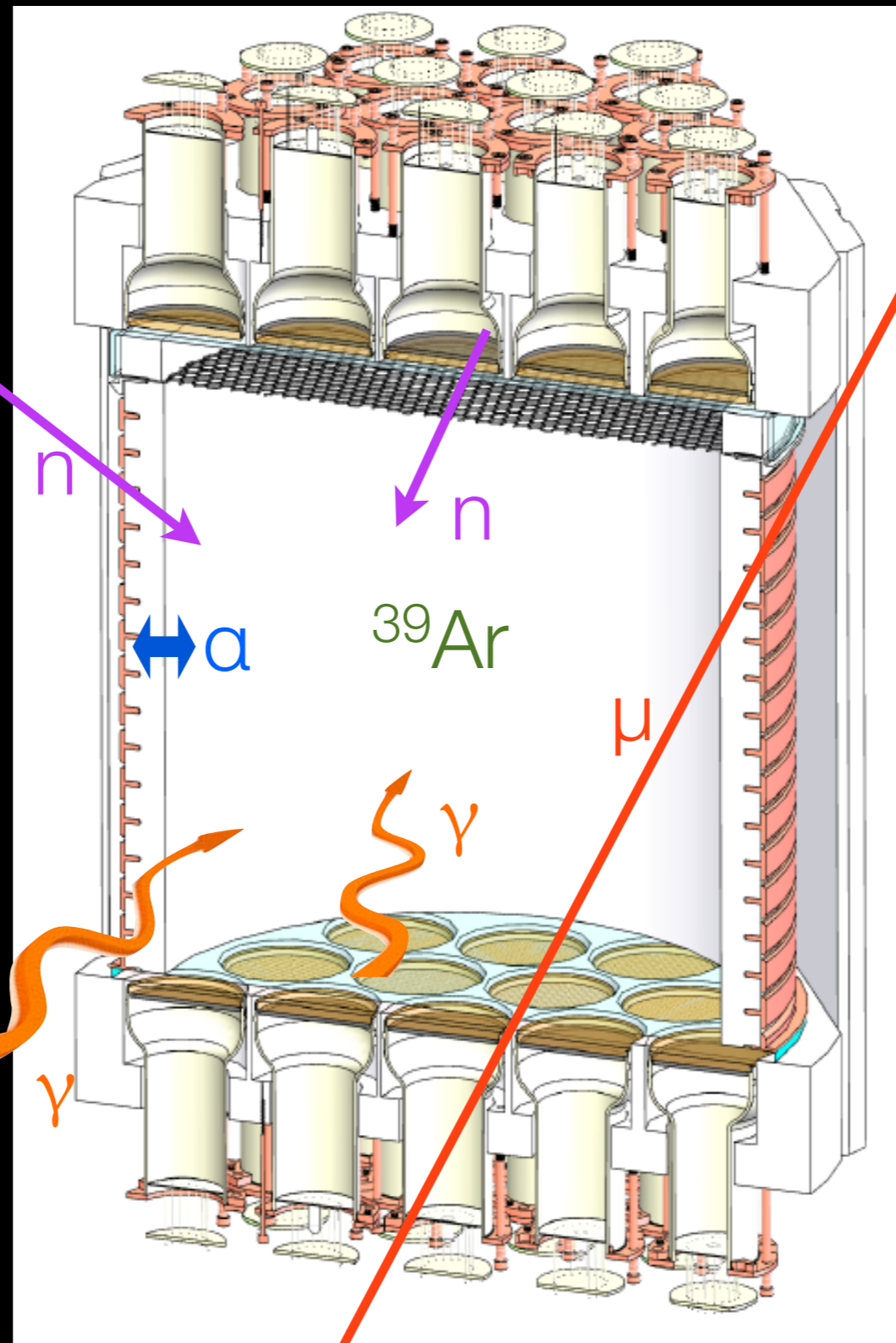
$\sim 30 \text{ evt/m}^2/\text{day}$

Radiogenic n

$\sim 6 \times 10^{-4} \text{ evt/kg/day}$

α

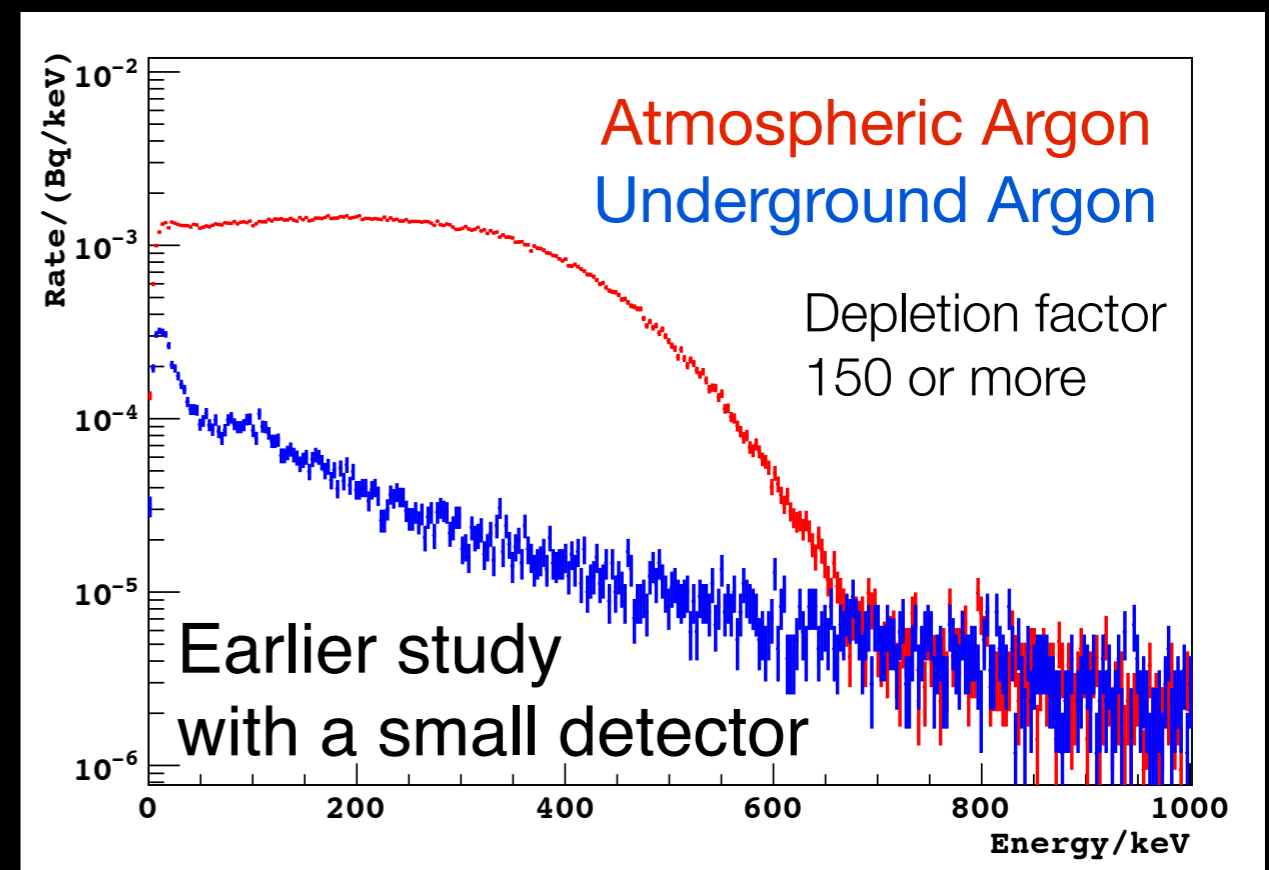
$\sim 10 \text{ evt/m}^2/\text{day}$



100 GeV, 10^{-45} cm^2 WIMP Rate $\sim 10^{-4} \text{ evt/kg/day}$

^{39}Ar

- Intrinsic ^{39}Ar radioactivity in **atmospheric argon** is the **primary background** for argon-based detectors
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is ineffective)
- ^{39}Ar is a **cosmogenic isotope**, and the activity in argon from **underground sources** can be significantly lower compared to **atmospheric argon**
- Recently DarkSide deployed underground argon. **Update will be at the end of this talk.**



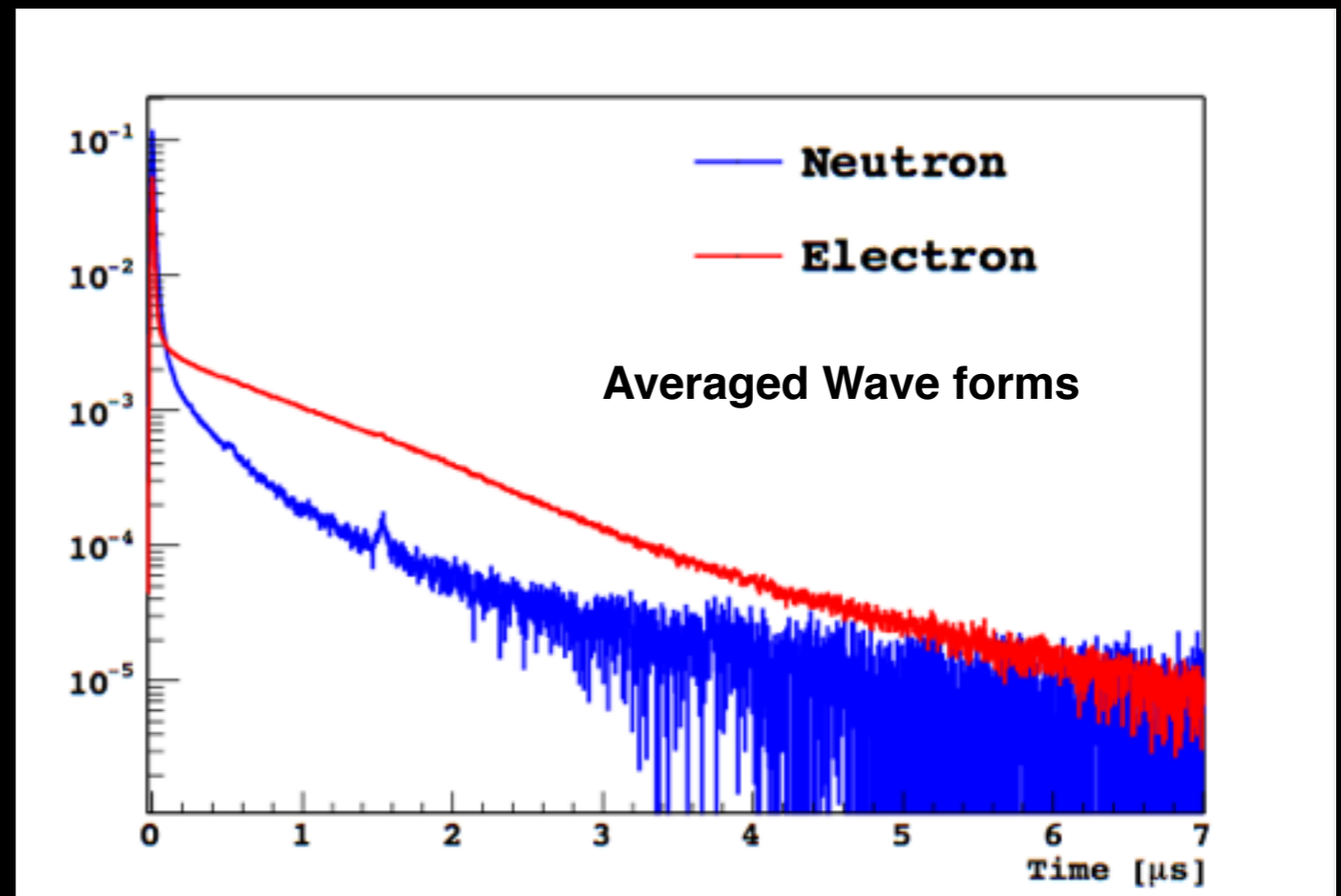
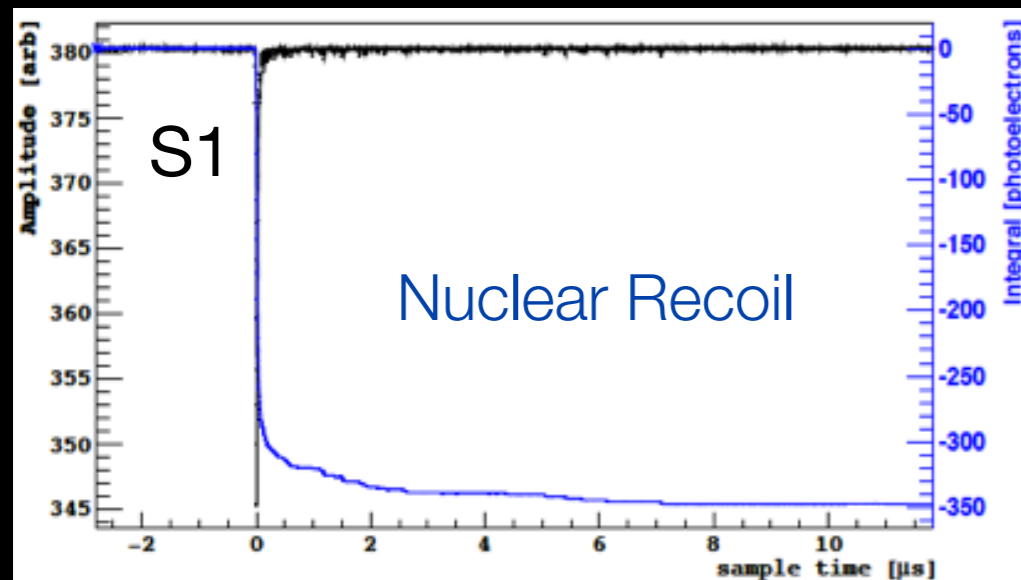
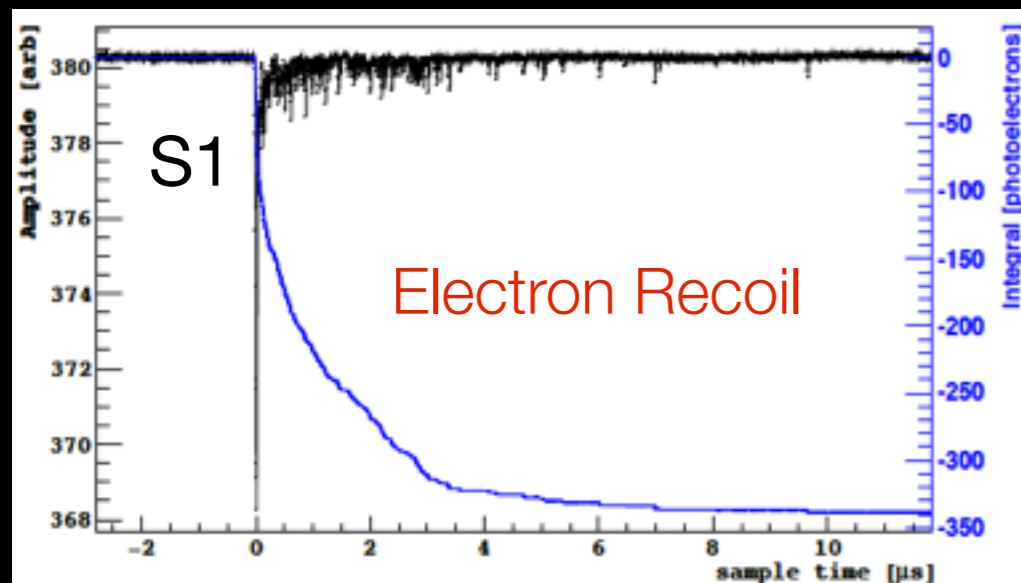
arXiv:1204.60111 [physics.ins-det]

Pulse Shape Discrimination

Electron Recoil Discrimination

Electron and nuclear recoils produce **different excitation densities** in the argon, leading to **different ratios of singlet and triplet excitation states**

$$\tau_{\text{singlet}} \sim 7 \text{ ns}$$
$$\tau_{\text{triplet}} \sim 1500 \text{ ns}$$



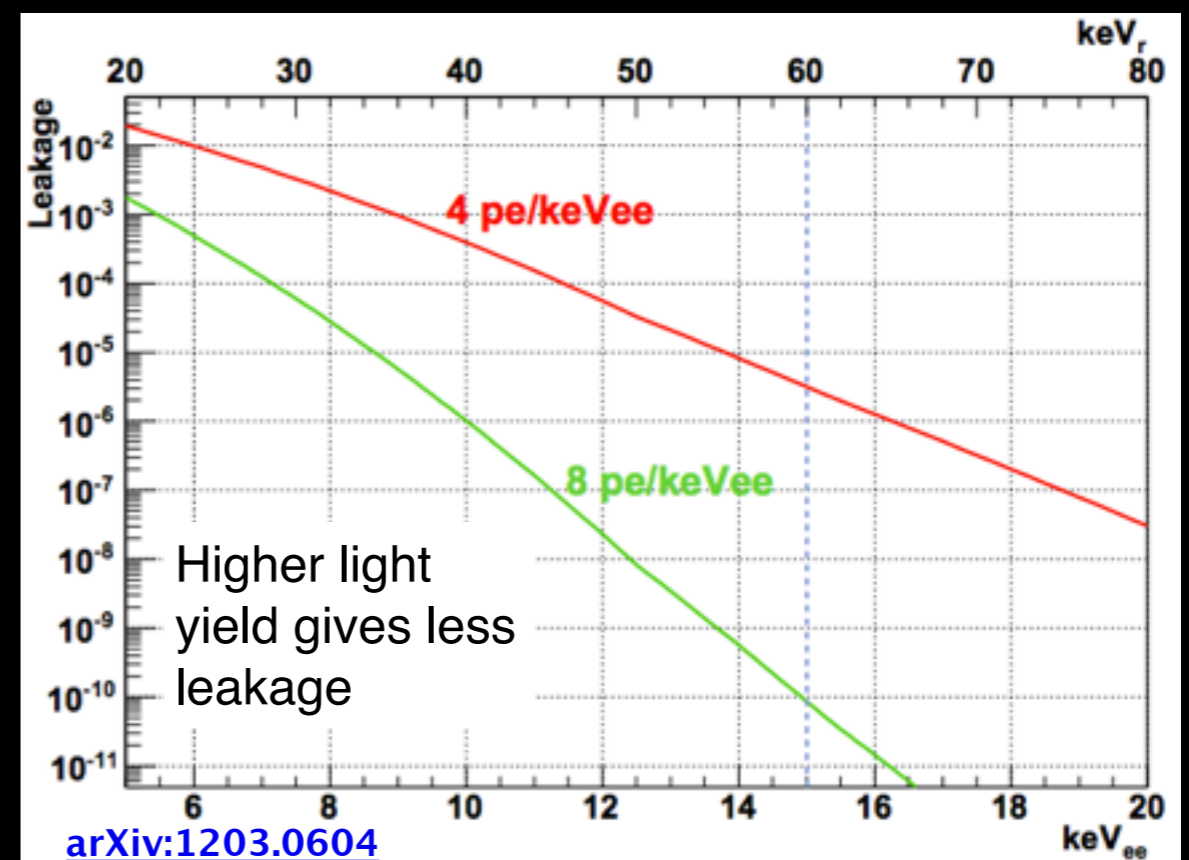
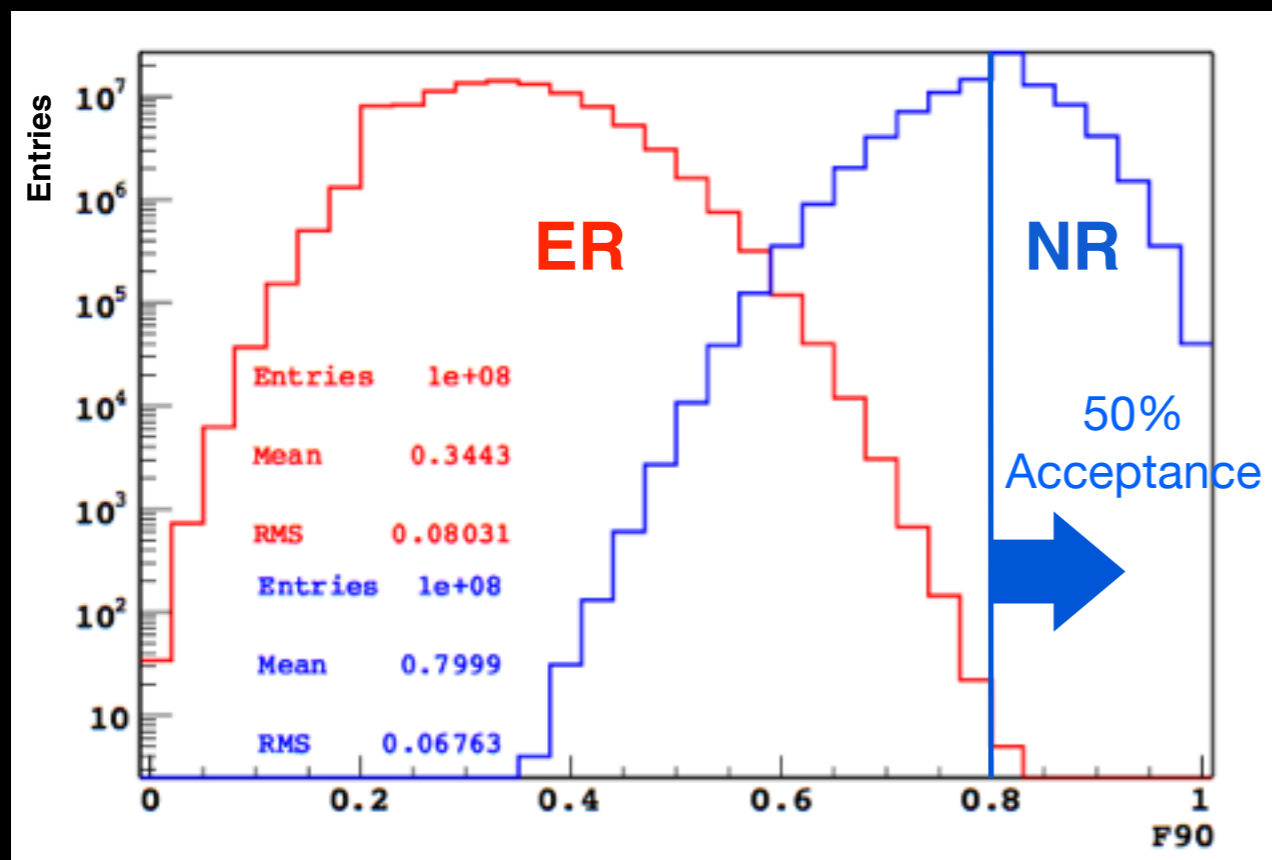
Pulse Shape Discrimination

Electron Recoil
Discrimination

F90: Ratio of detected light in the first 90 ns,
compared to the total signal ~ **Fraction of singlet states**

$\tau_{\text{singlet}} \sim 7 \text{ ns}$

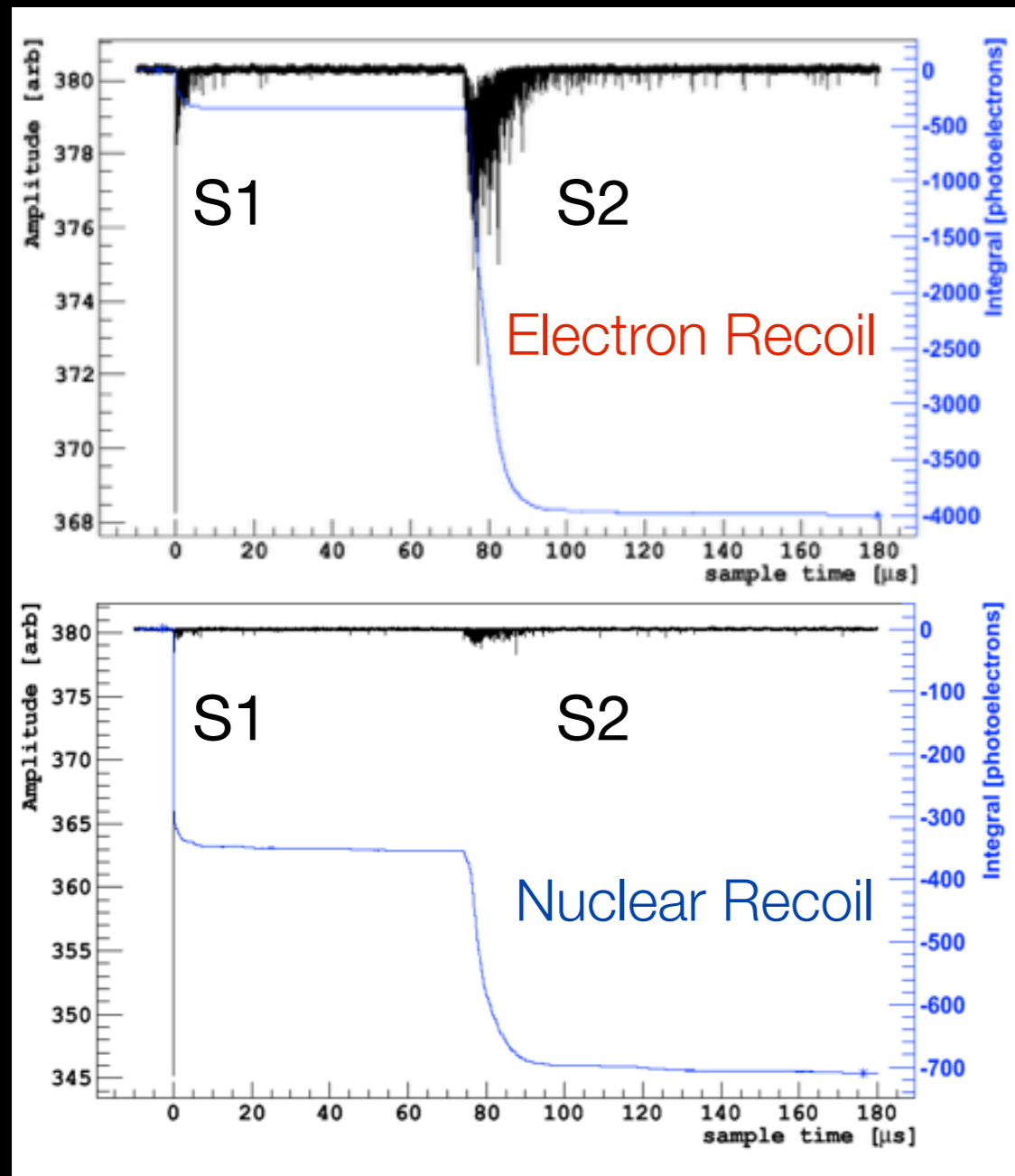
$\tau_{\text{triplet}} \sim 1500 \text{ ns}$



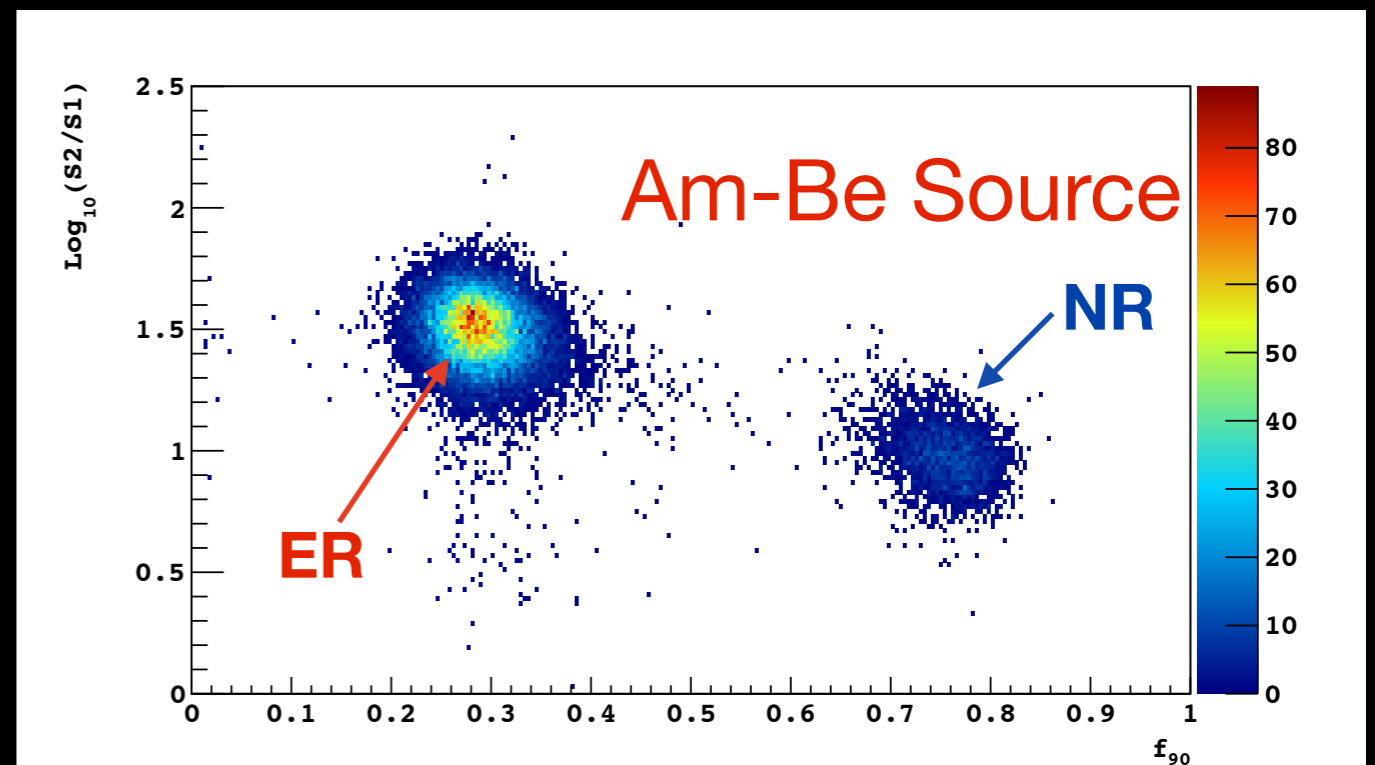
Discrimination power strongly dependent on **light collection**

S2/S1

Electron Recoil Discrimination



Electron and **nuclear** recoils produce different **ionization densities** that lead to different fractions of electrons that survive recombination

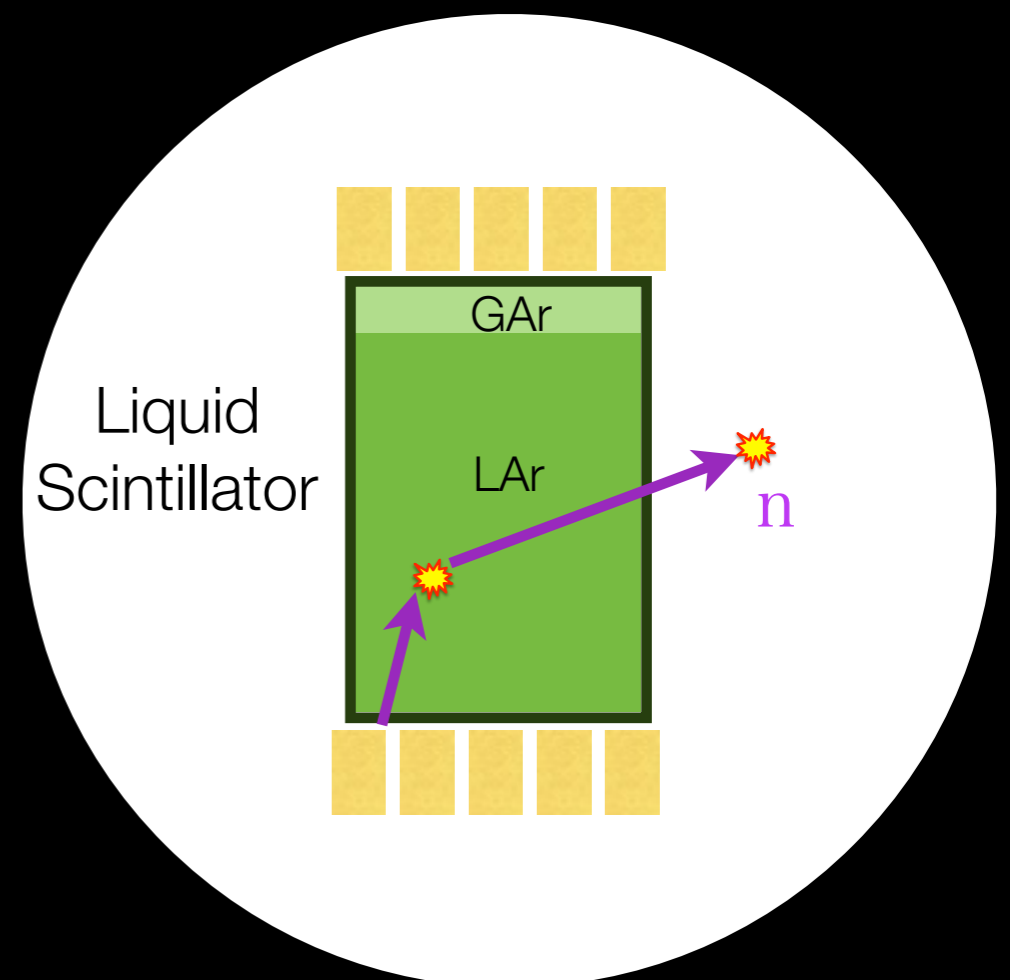
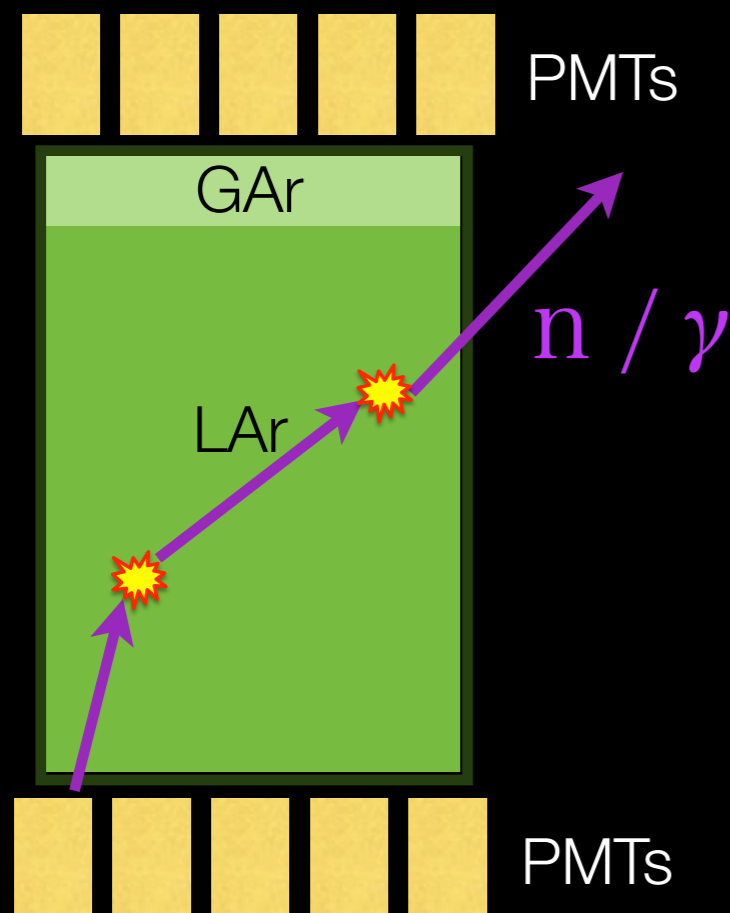


Ratio of ionization and scintillation signal (S2/S1) can be used to distinguish between the two populations

Multiple Interactions

Neutron
Rejection

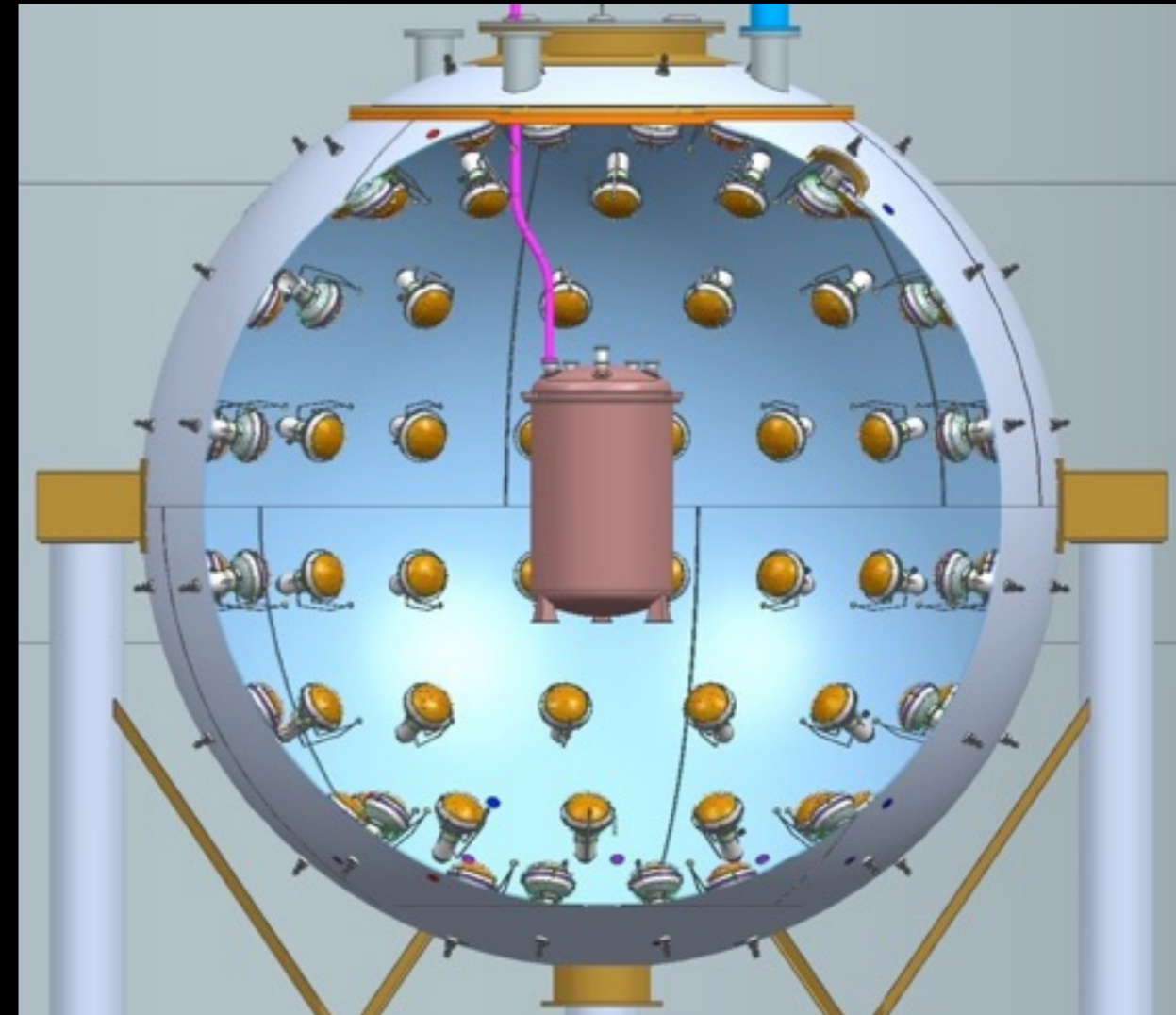
Expected WIMP signal	Background Rejection Technique	Backgrounds Removed
Single Interaction	Multiple S2 Cut in TPC Liquid Scintillator Veto	Neutrons, Gamma rays



Liquid Scintillator Veto

Liquid scintillator allows coincident veto of **neutrons (and γ 's)** in the TPC and provides *in situ* measurement of the neutron background rate

- 4 m diameter sphere containing PC + TMB scintillator
- Instrumented with 110 8" PMTs

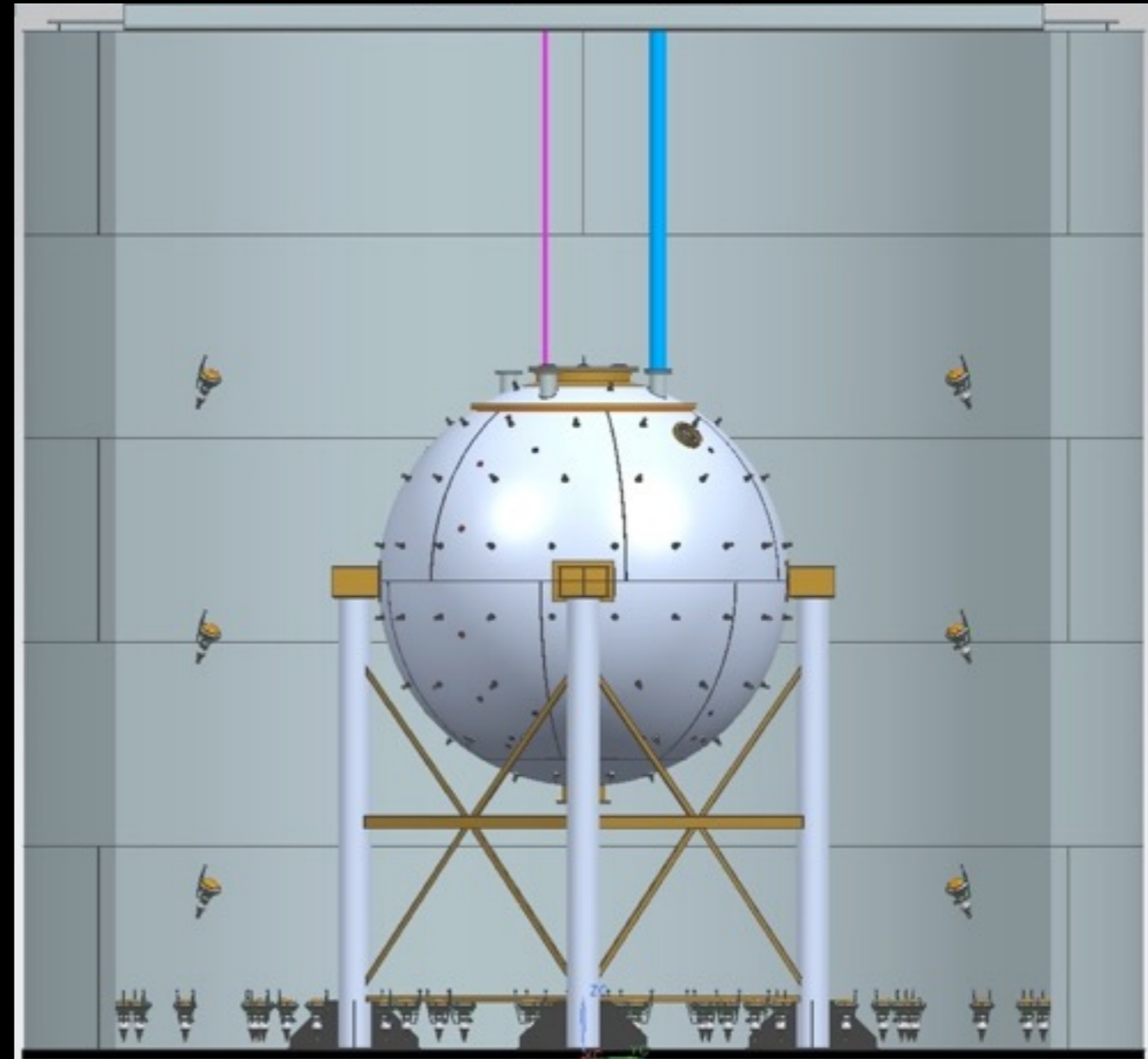


Odd time structure: ^{14}C content is too high (~98% efficiency) to achieve design efficiency (~99.5%) after the first fill.

The TMB was replaced with new low ^{14}C TMB (Jan. 2015). ^{14}C activity decreased from **150 kBq** to **0.3 kBq**.

External Water tank

- 80 PMTs within water tank (11 m diameter x 10 m height)
- Acts as a **muon and cosmogenic veto** (~ 99% efficiency)
- Provides **passive γ 's and neutron shielding**



Radon-Free Clean Rooms

Surface
contamination

Radon daughters plate out on surfaces of the detector causing dangerous alpha-induced nuclear recoils.

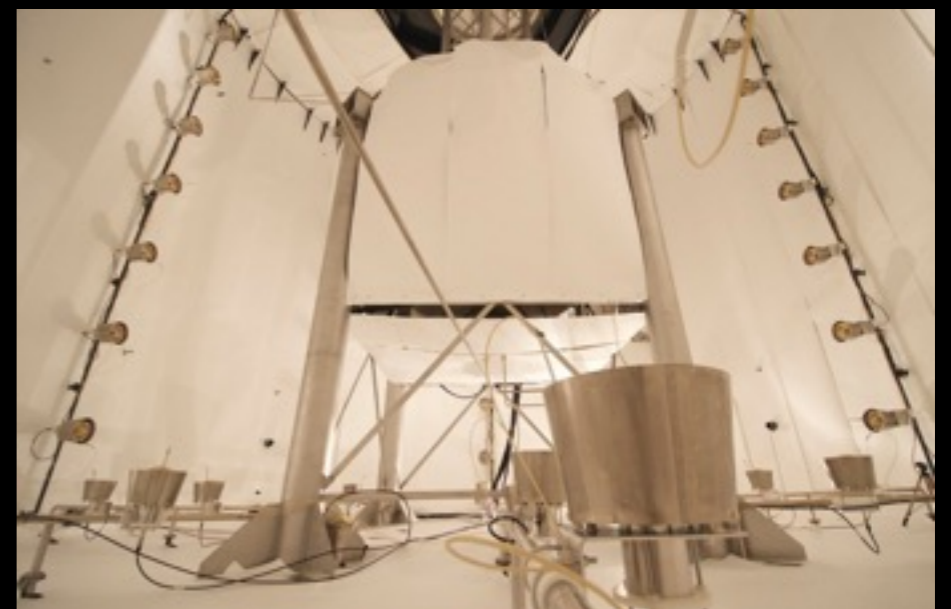
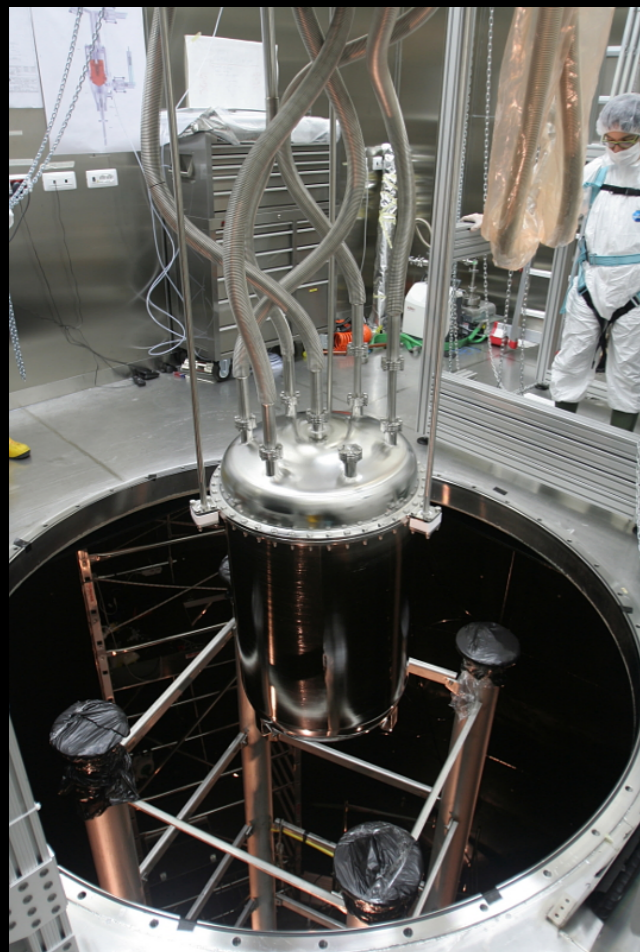
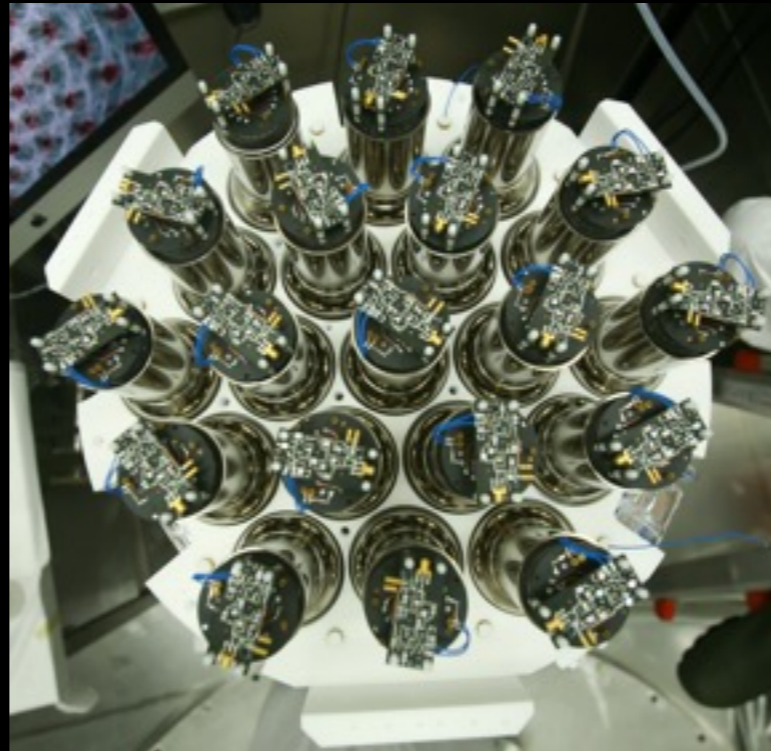
Final preparation, cleaning, evaporation and assembly of all inner detector parts was carried out in radon-free clean rooms.



Typical radon in air ~ 30 Bq/m³

Cleanroom radon levels < 5 mBq/m³

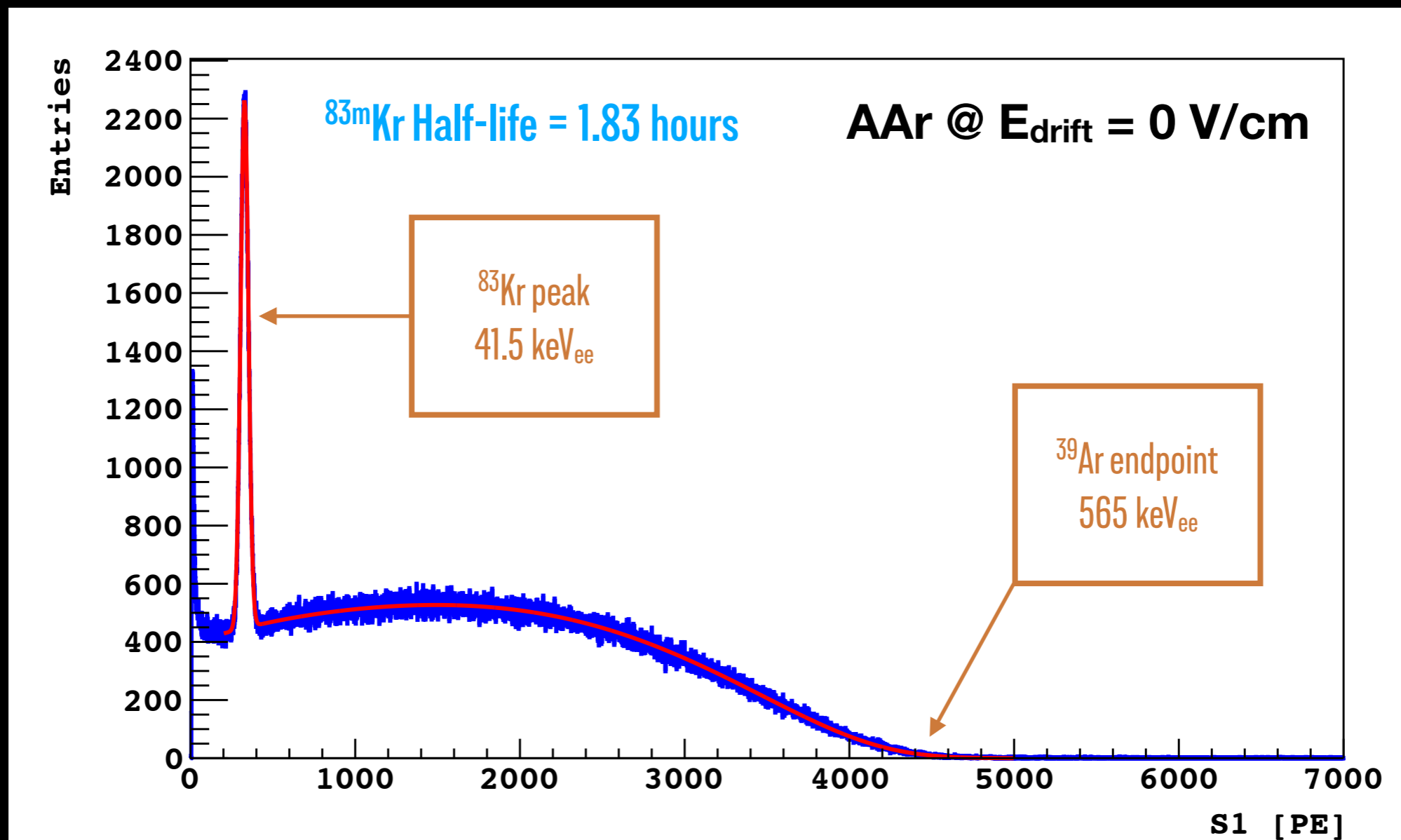
DS50 Commissioning



TPC Calibration

TPC: Electric Recoils calibration

- ^{39}Ar (565 keV_{ee} endpoint) present in AAr
- $^{83\text{m}}\text{Kr}$ gas deployed into detector (41.5 keV_{ee})



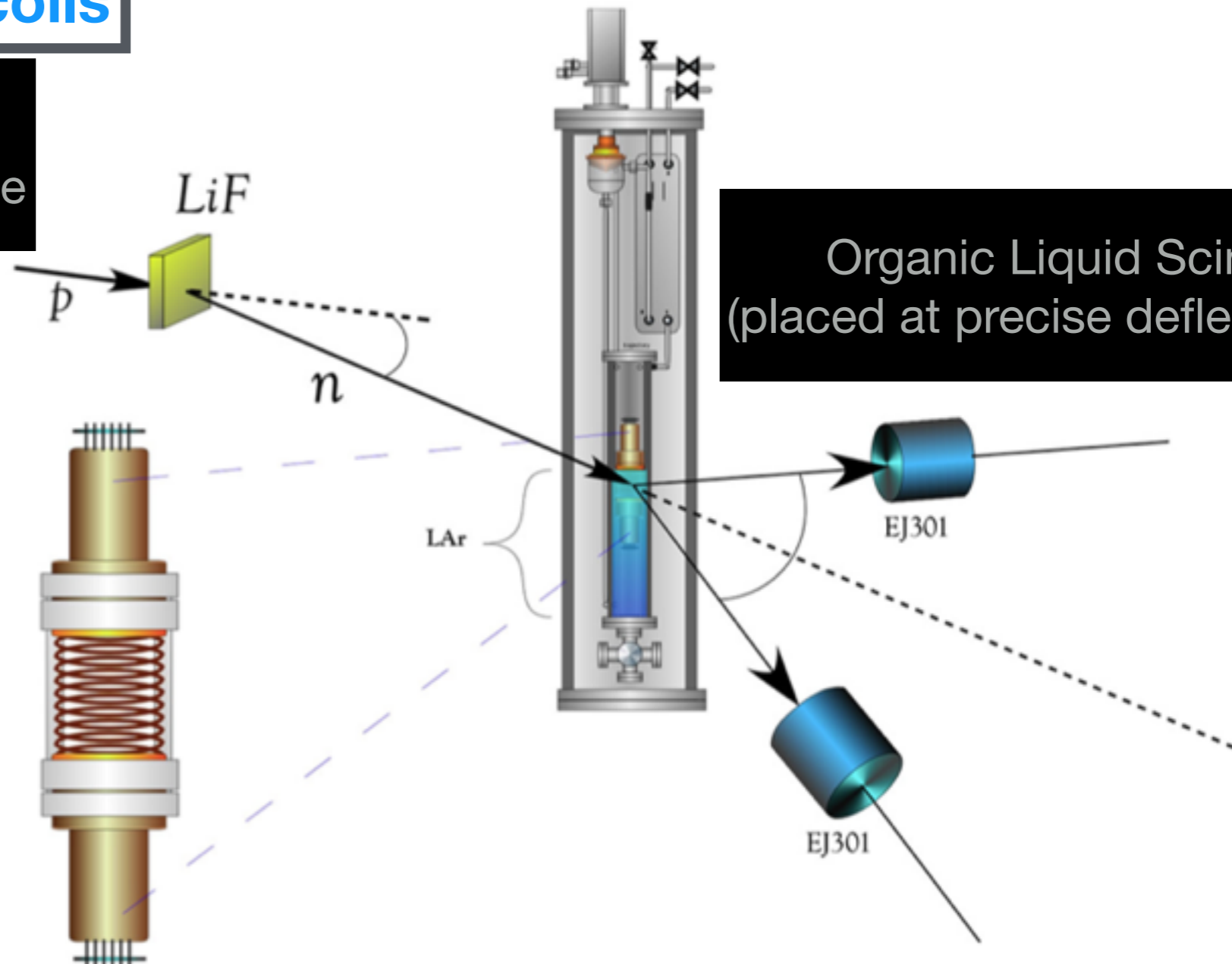
Fits to ^{39}Ar and $^{83\text{m}}\text{Kr}$ spectrum indicate
LIGHT YIELD: 7.9 ± 0.4 PE/keV_{ee} at zero field and 7.0 ± 0.3 PE/keV_{ee} at 200 V/cm

SCENE

(Scintillation Efficiency of Nuclear Recoils in Noble Elements)

For Nuclear Recoils

Proton Beam at
University of Notre Dame



Liquid Argon TPC
(based on DarkSide
design)

Organic Liquid Scintillators
(placed at precise deflection angles)

EJ301

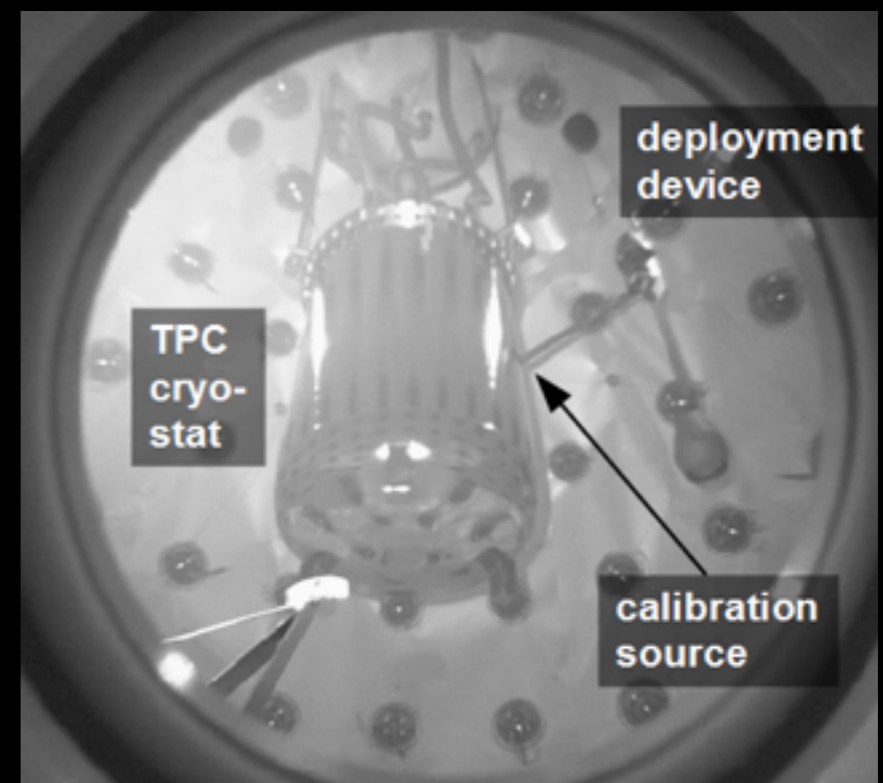
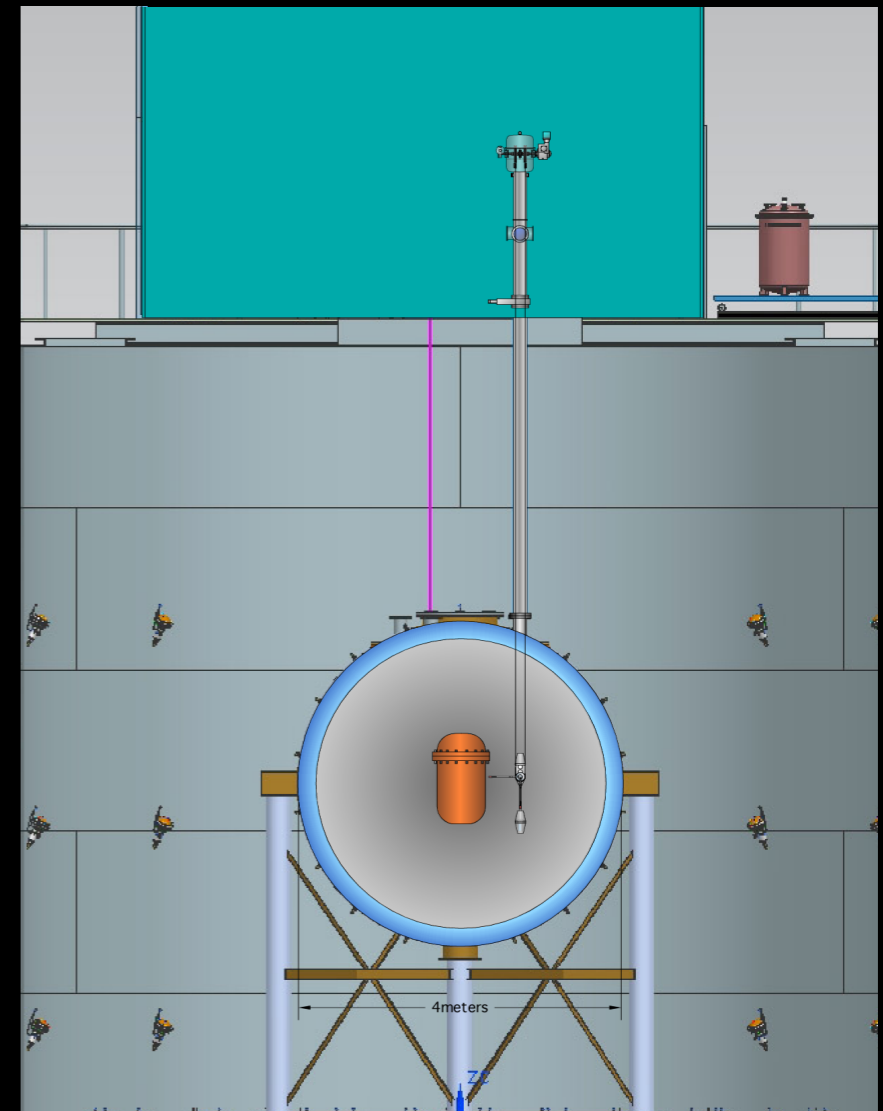
EJ301

${}^7\text{Li}(p, n){}^7\text{Be}$ reaction produces low energy monoenergetic neutrons
TOF measurement between target, LAr and organic scintillators allows
clean identification of elastic neutron interactions of known energy

CALIS - CALibration Insertion System

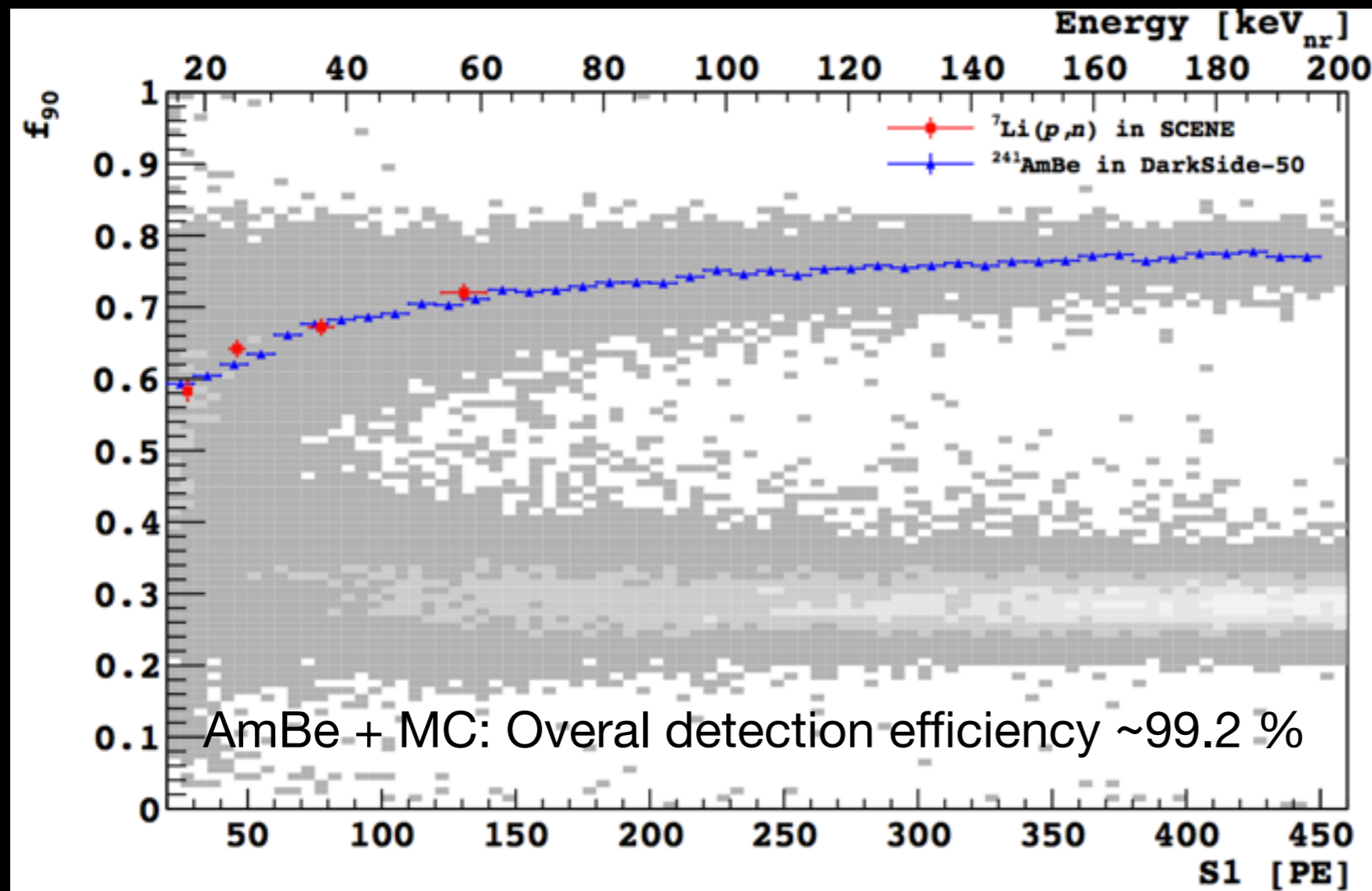
Calibrate both **TPC** and **Neutron veto**

- **Gamma sources:** ^{57}Co (122 keV), ^{133}Ba (356 keV), ^{137}Cs (663 keV)
- **Neutron source:** AmBe w/ and w/o collimator
- **Different drift fields:** null, 100 V/cm, 150 V/cm, 200 V/cm

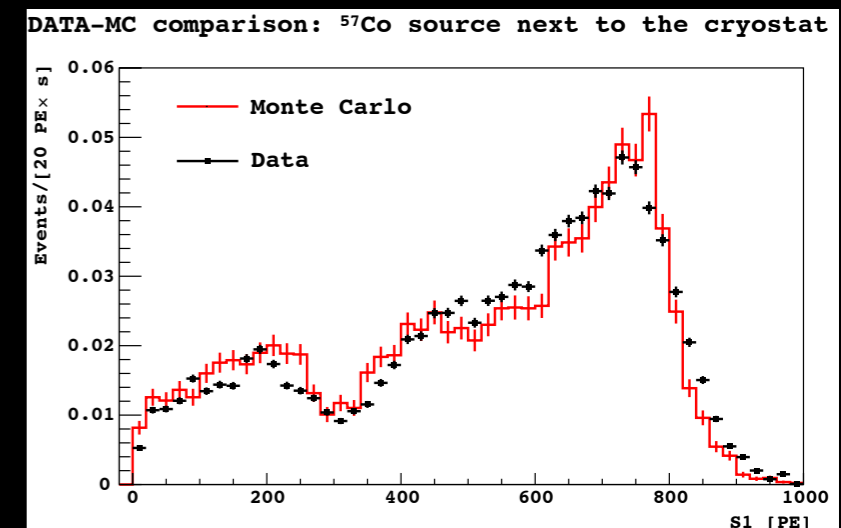


NR from AmBe source

NR band study (crosscheck of SCENE data).

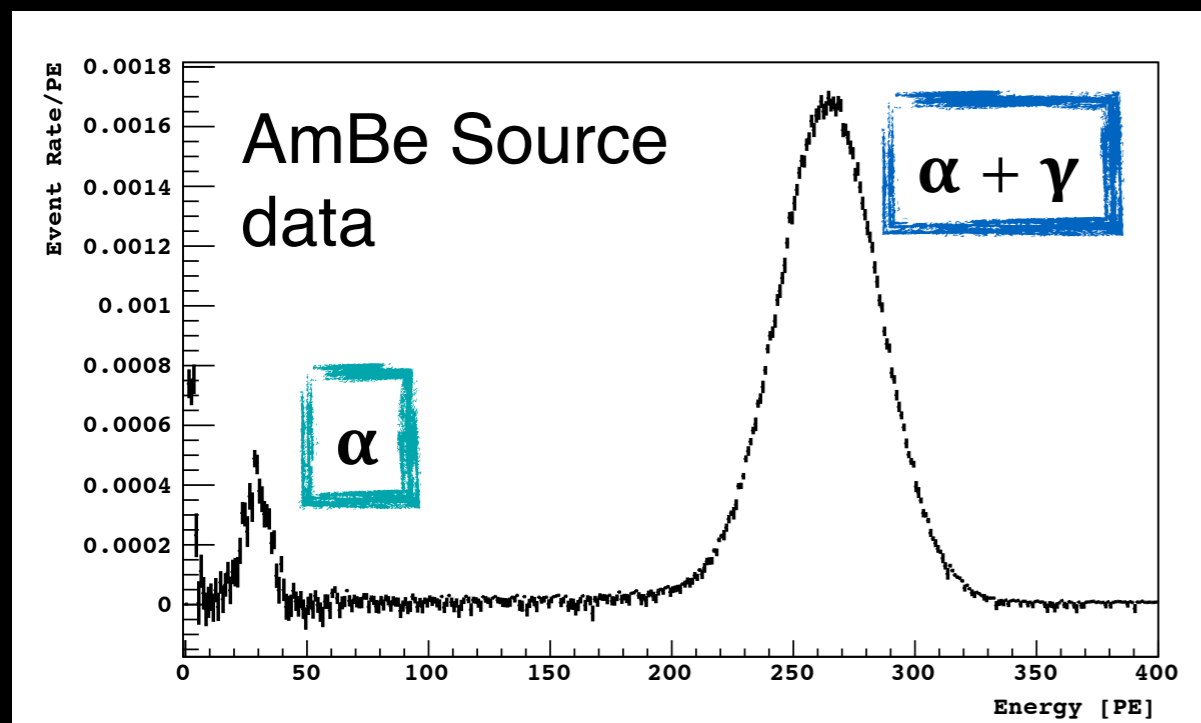
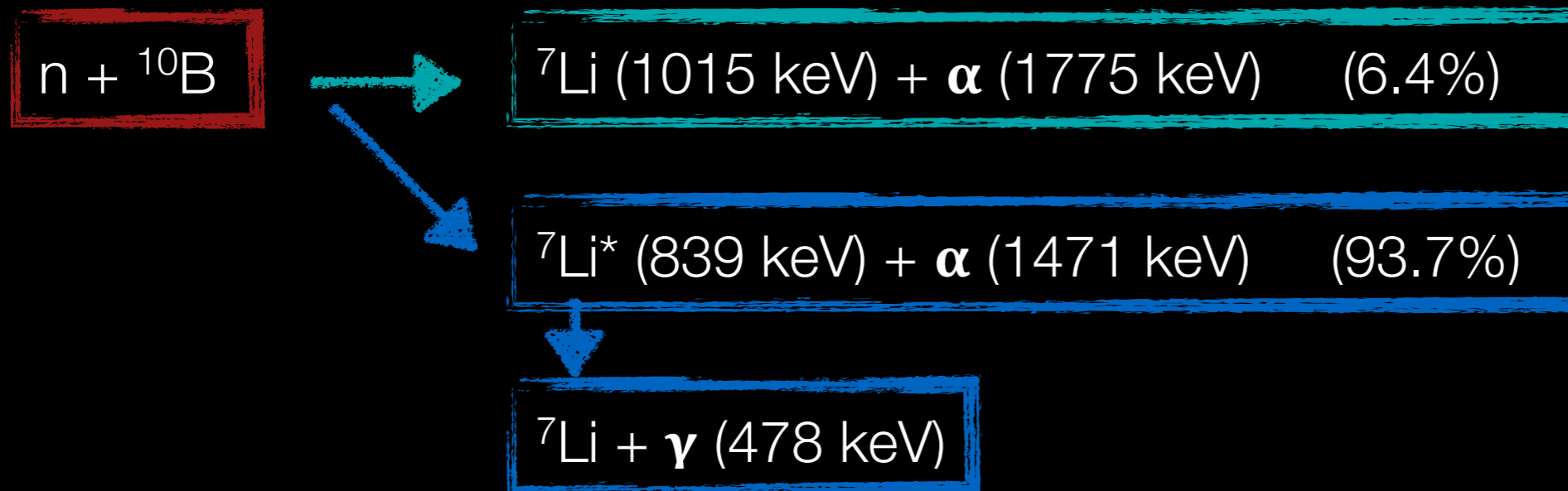


Deep test of the GEANT4 MC code.



NR band matches with the points extrapolated from SCENE.

Neutron Capture (Veto)



Veto efficiency from capture signal > 99%
(from calibrations and simulations)

- $\sim 7.7\%$ of capture on ^1H ; 2.2 MeV γ lost $\sim 8\%$
- $\sim 0.05\%$ of neutrons leave no signal in LSV at all

Total Veto efficiency is larger due to additional thermalization signal

Due to low background, only $\sim 0.9\%$ acceptance loss with 1 PE threshold

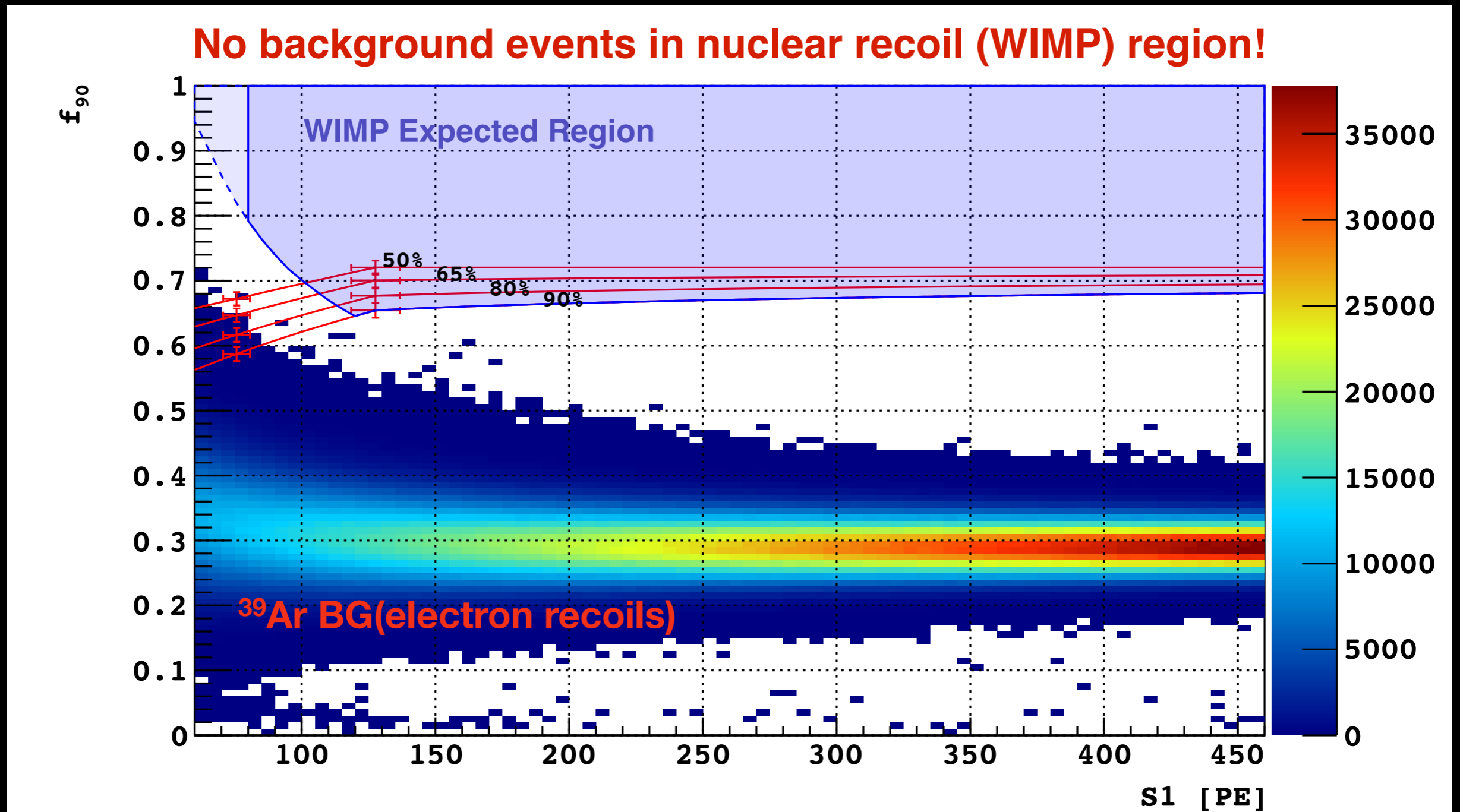
DS50 Timeline

- **Oct. 2013:** LArTPC, Neutron Veto and Muon Veto commissioned.
 - TPC filled with **atmospheric argon** (AAr).
- **Up to June 2014:** data taken with high ^{14}C content in LSV.
 - **47.1 live days** (1422 kg · day fiducial) for the first physics result.
 - TMB (^{14}C) was removed to reduce the ^{14}C rate.
- **Oct. to Dec. 2014:** Calibration of TPC w/ radioactive sources.
- **Jan. 2015:** Add radiopure TMB at 5% concentration.
- **Mar. to Apr. 2015:** Fill with **UAr** and re-commissioning the detector.
- **Apr. to Aug. 2015:** Accumulate data with **UAr** for **dark matter search**.

The First Physics Result from DS-50

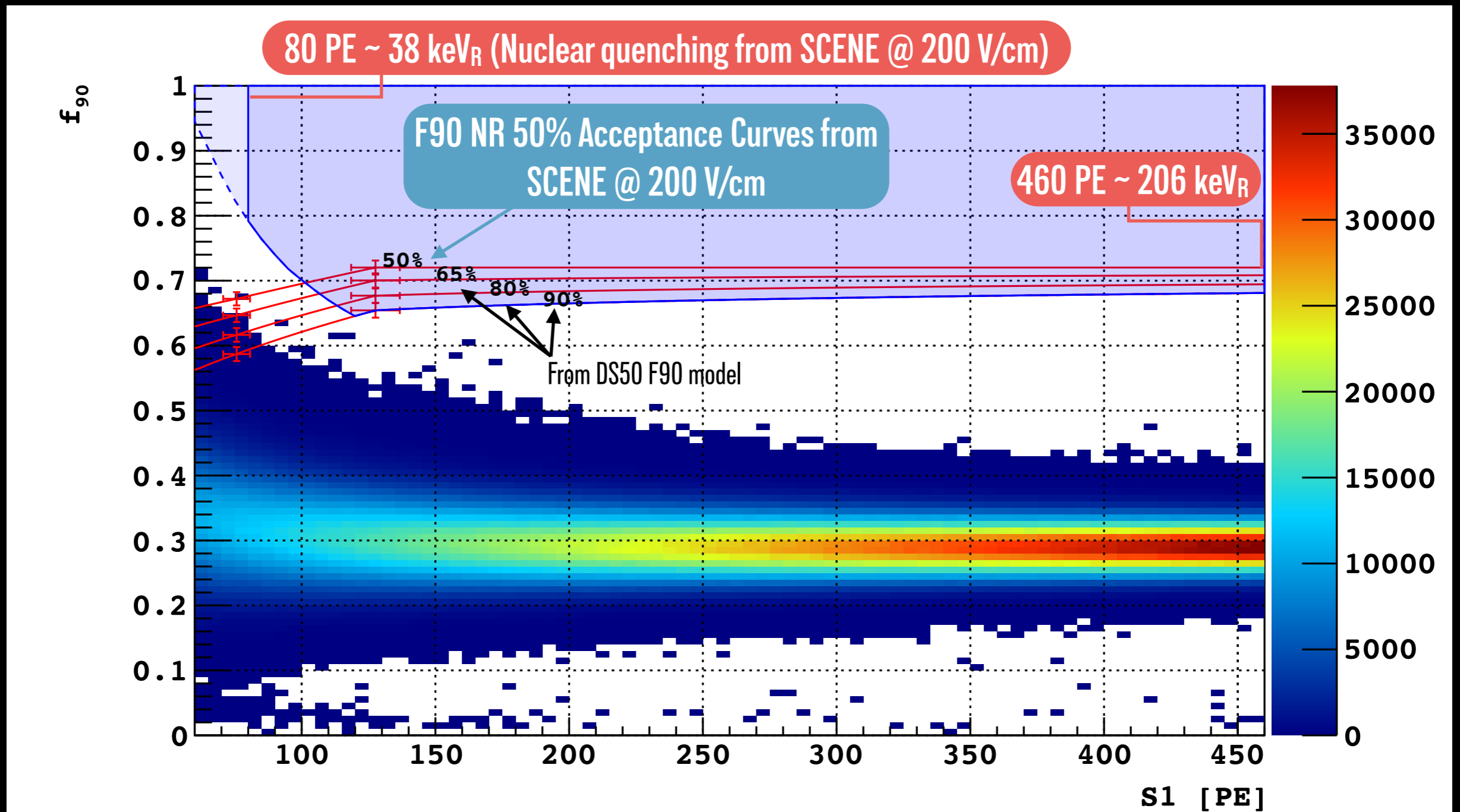
Background-free exposure of $1422 \pm 67 \text{ kg} \cdot \text{day}$

Phys. Lett. B 743 (2015) 456



Selected only single-hit interactions in the TPC fiducial volume (36.9 kg) with no energy deposition in the veto

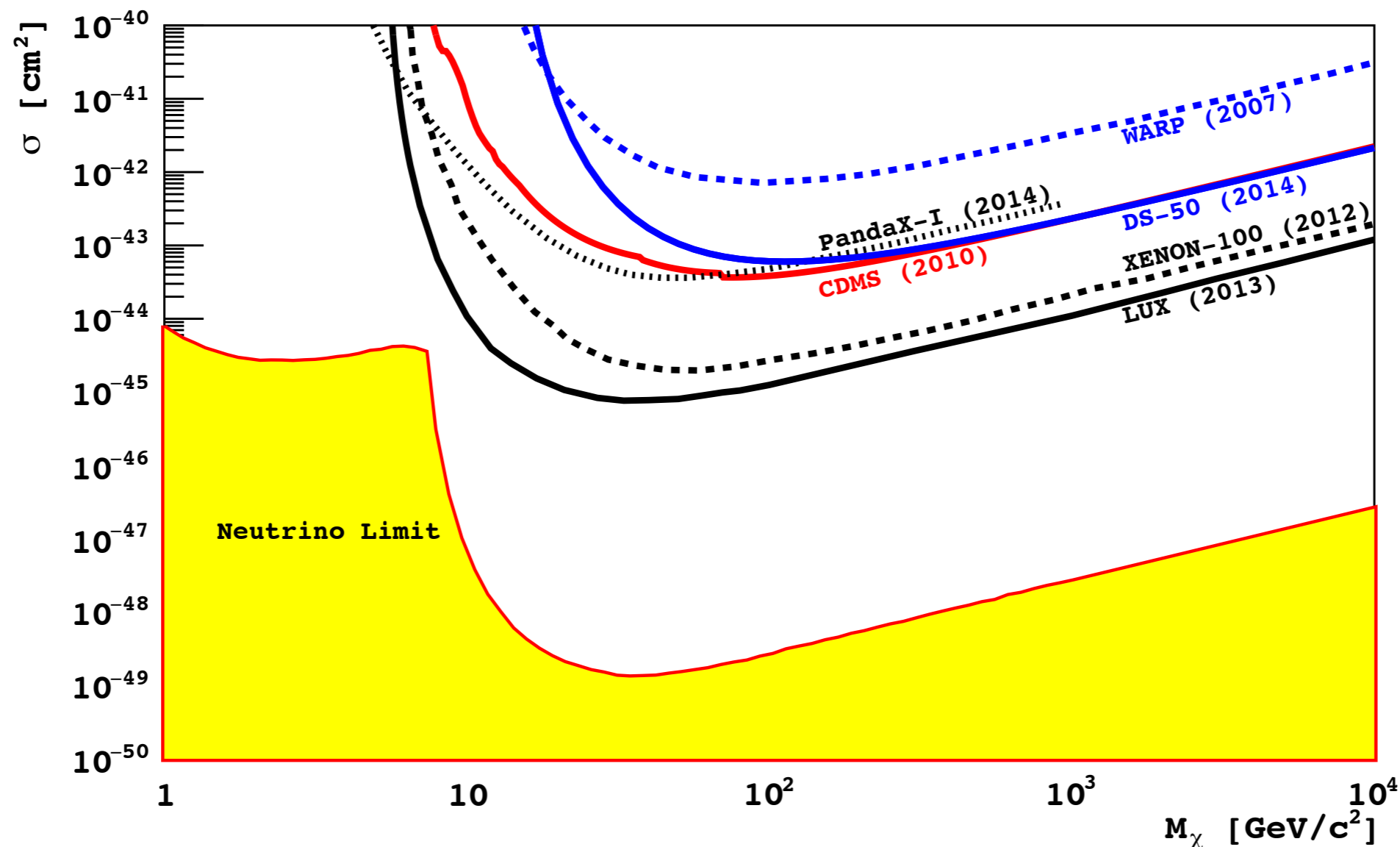
Background-free exposure of $1422 \pm 67 \text{ kg} \cdot \text{day}$



Selected only single-hit interactions in the TPC fiducial volume (36.9 kg) with no energy deposition in the veto

Dark Matter exclusion plot

This is the most sensitive dark matter search performed with an **argon** target. The WIMP-nucleon spin-independent cross section is $6.1 \times 10^{-44} \text{ cm}^2$ for a WIMP mass of $100 \text{ GeV}/c^2$.



Underground Ar



Plant at Colorado

1. Extraction at Colorado (CO_2 Well)
Extract a crude argon gas mixture
(Ar and He)

2

at Fermilab

Ar from He and N_2



UAr bottles at LNGS

3. Arrived at LNGS
Ready to fill into DS-50

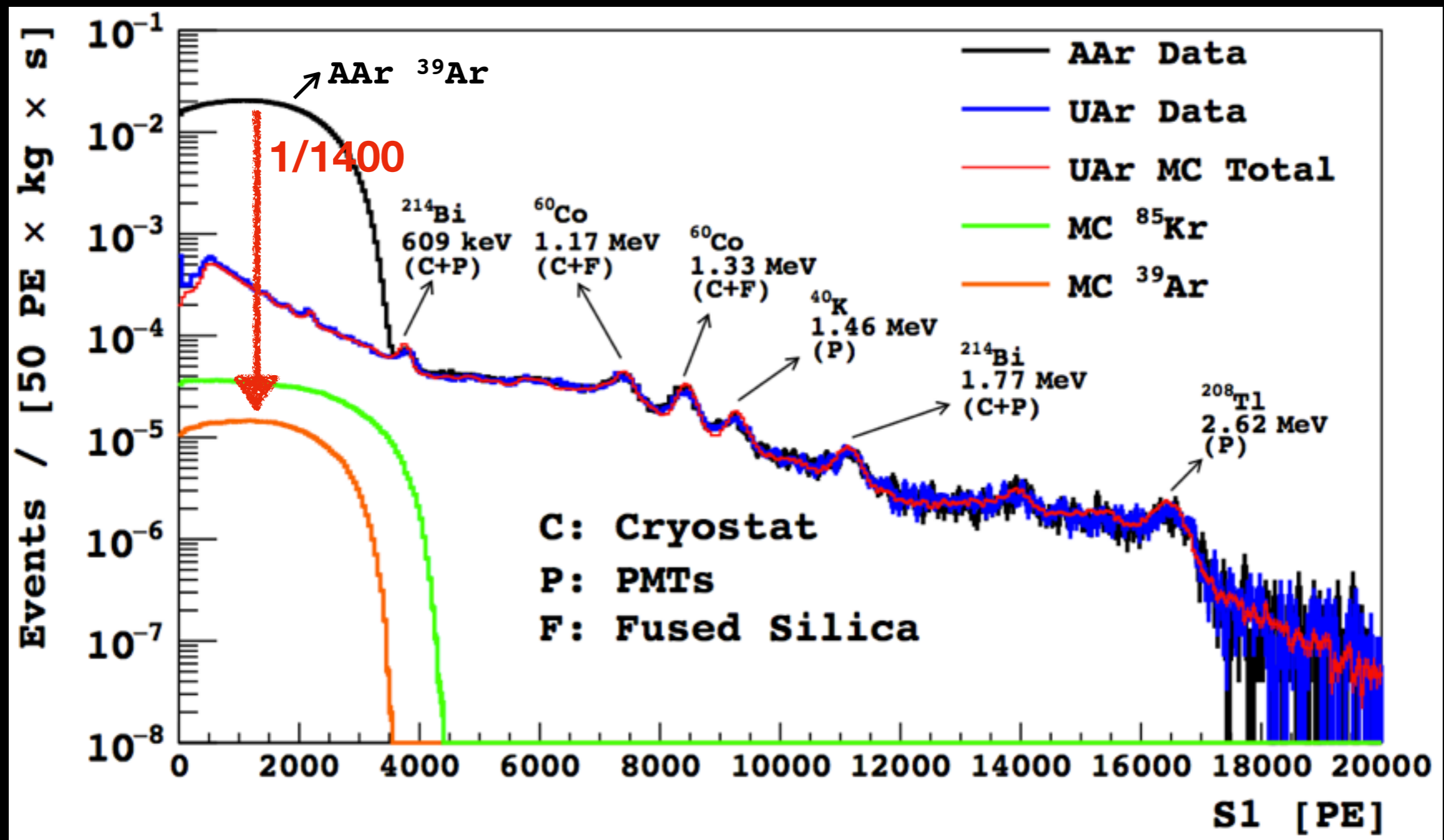


Distillation Column at
Fermilab

UAr First Results

AAr vs UAr. Live-time-normalized S1 pulse integral spectra at **Zero** field.

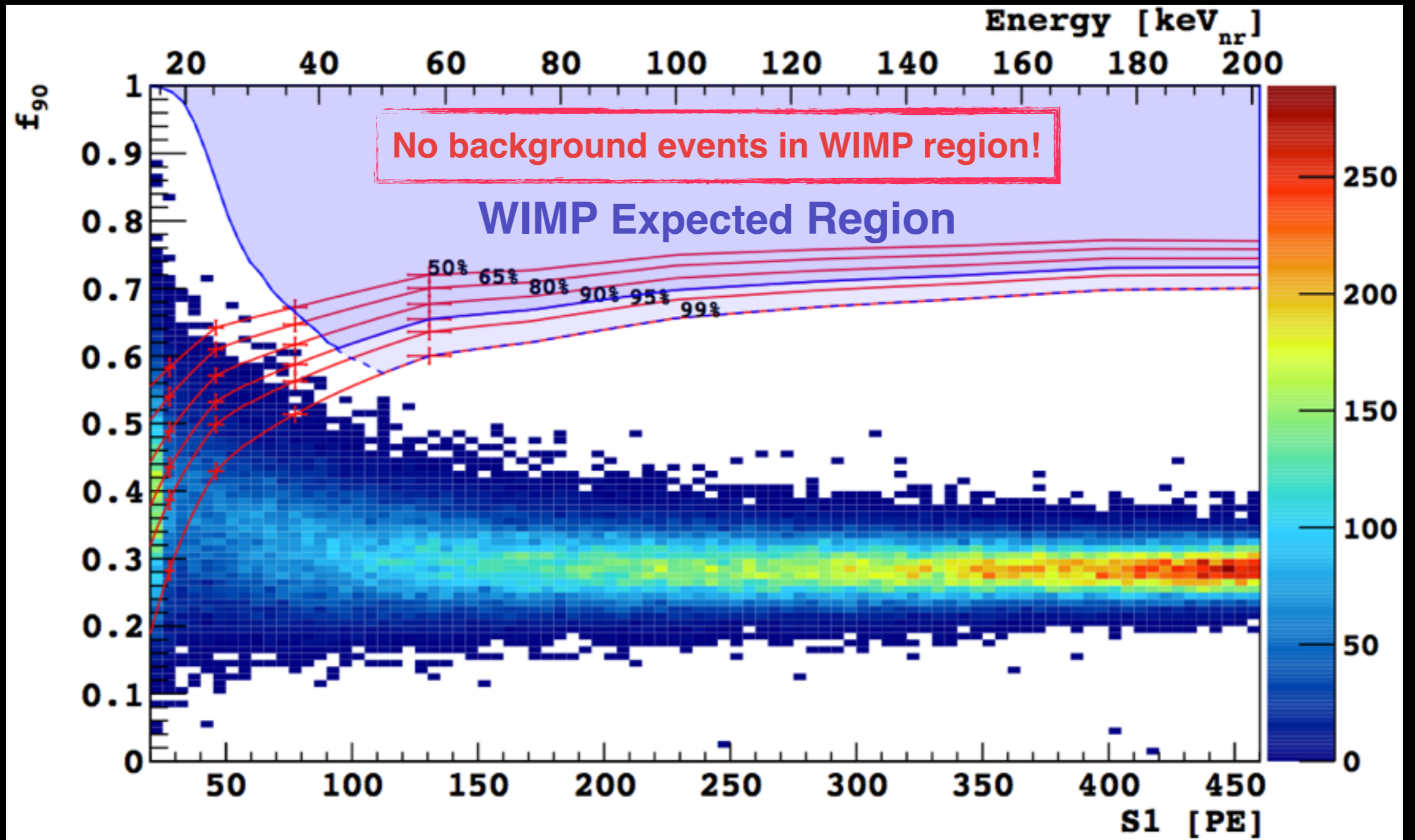
^{39}Ar reduction factor of **~1400!**



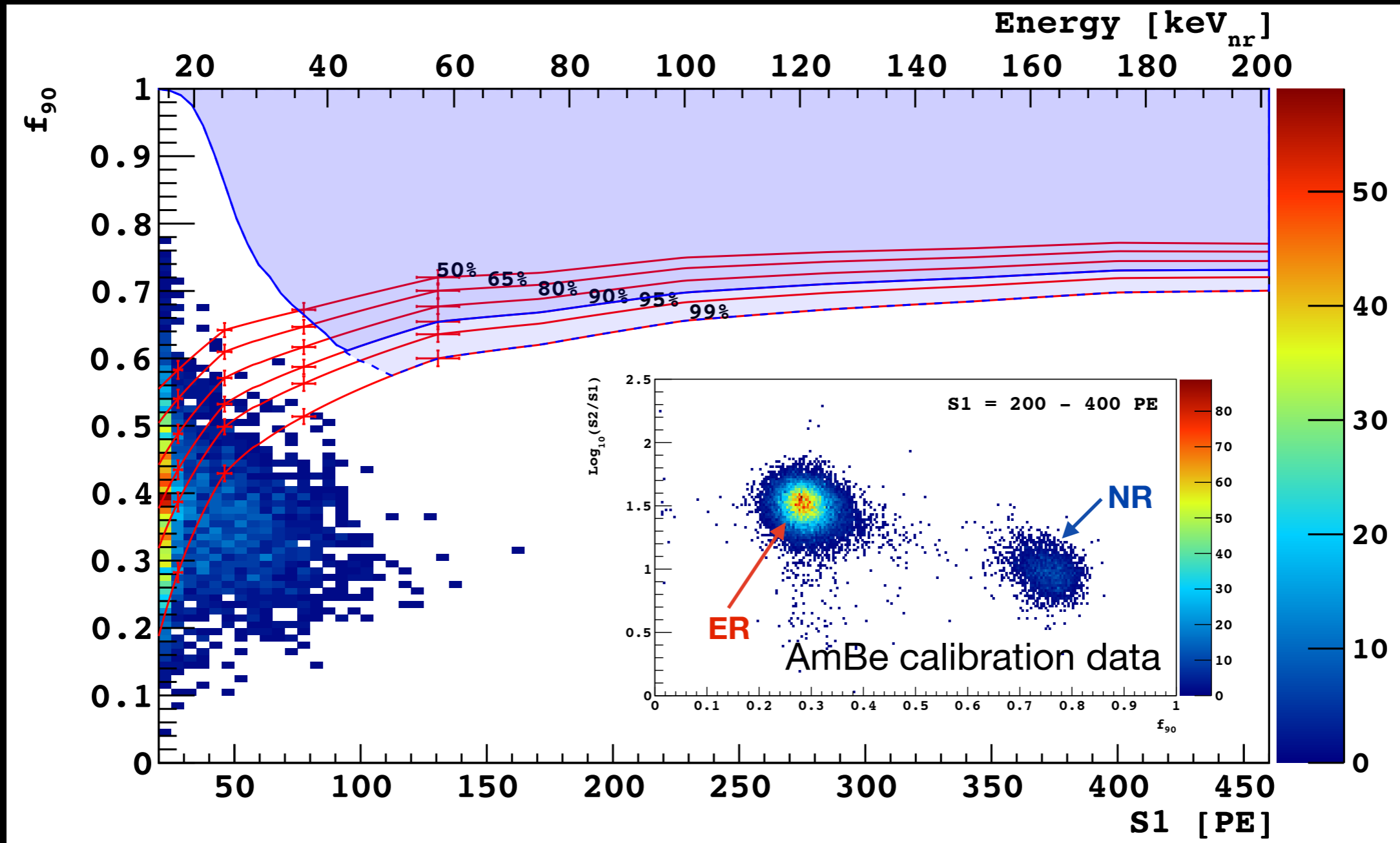
Low level of ^{39}Ar allows extension of DarkSide program to **ton-scale** detector.

UAr First Results

71 live-days after all cuts. (2616 ± 43) kg day exposure.
Single-hit interactions in the TPC, no energy deposition in the veto.

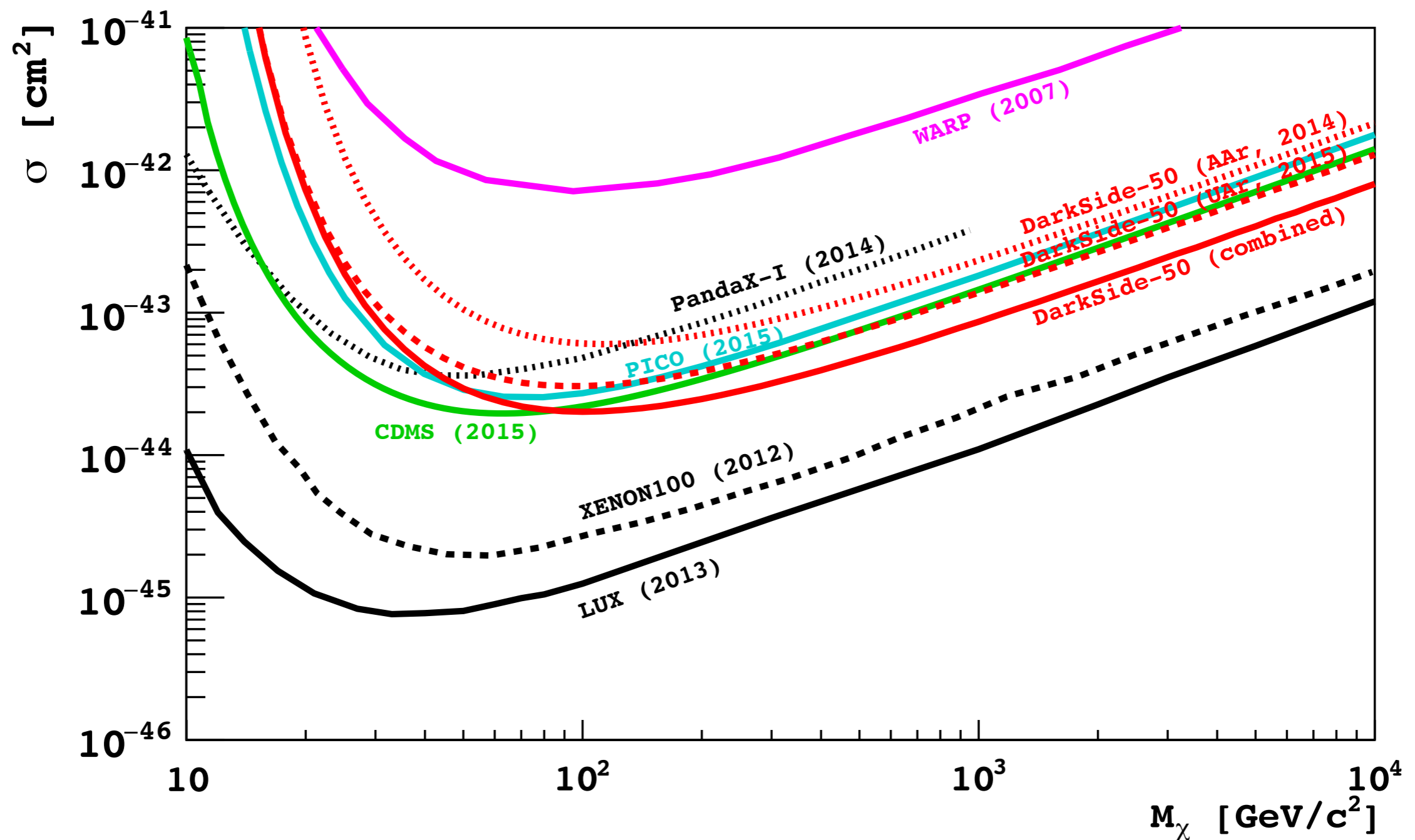


UAr First Results w/ S2/S1 cut



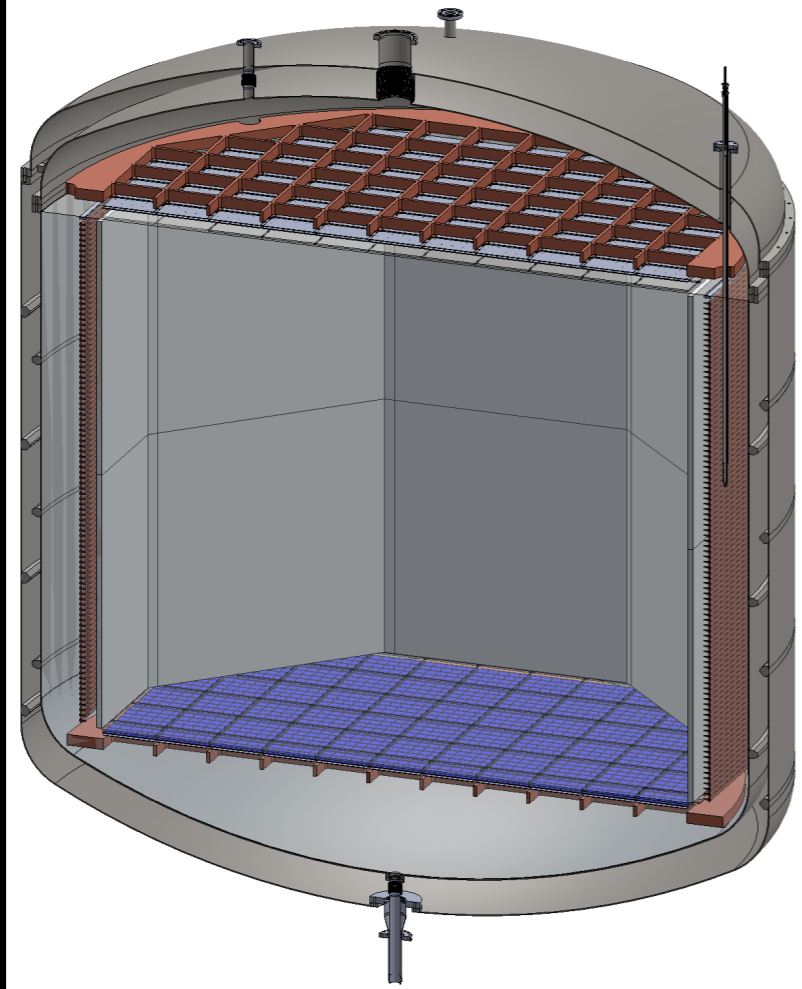
We have another discrimination power to suppress ERs (S2/S1 cut w/ 50% acceptance of NRs).

UAr First Results



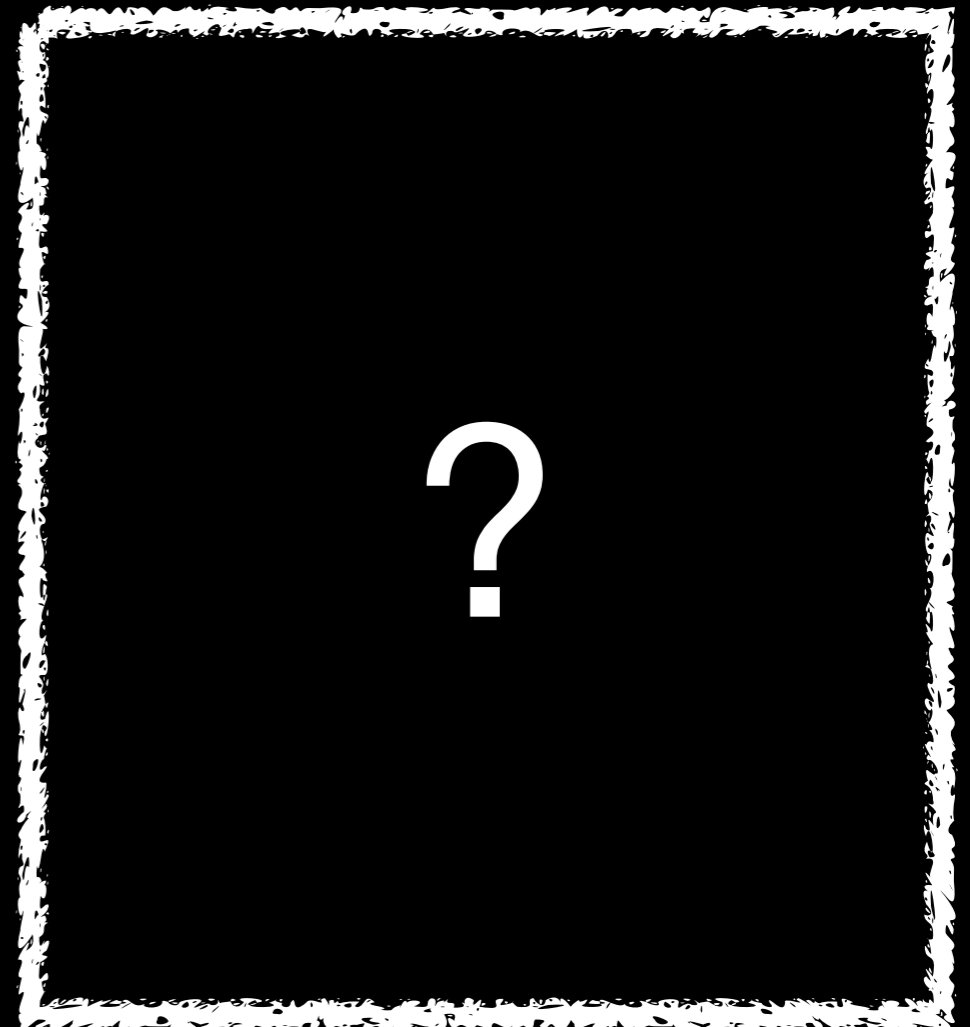
Best limit to date, with argon target, third best limit behind LUX & Xenon100.

Future Detectors



DS-20k

30 tonne (20 tonne fiducial) detector



ARGO

300 tonne (200 tonne fiducial) detector

Requirements for DS-20k

Neutron Background:

- **Cosmogenic**: Veto system
- **Radiogenic**: radiopure SiPM & ultra-clean Titanium (TPC cryostat)

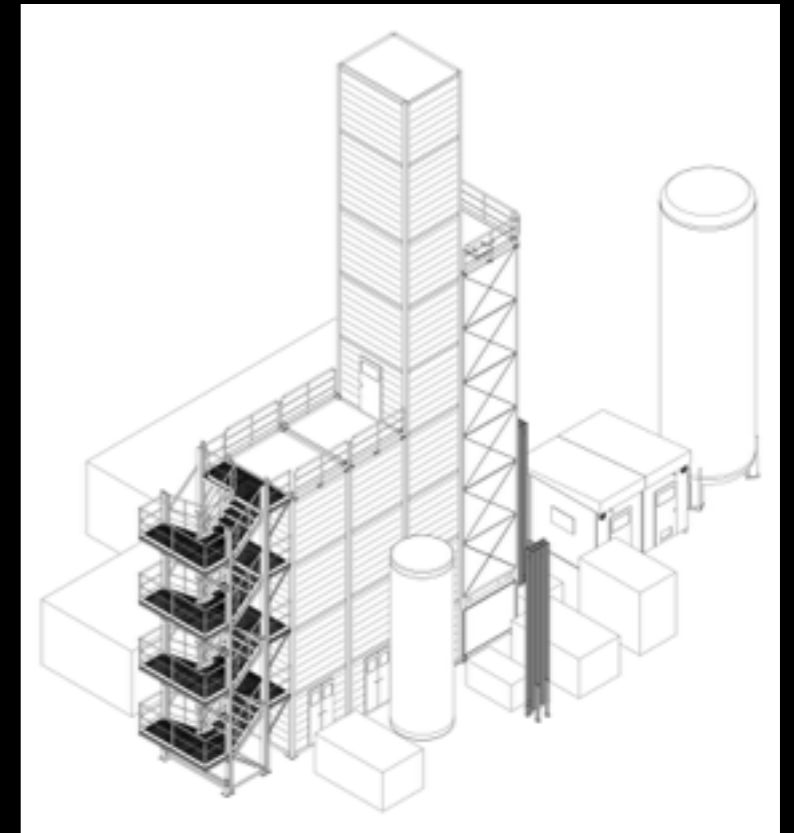
β/γ background:

- **^{39}Ar** : Underground Argon (Urania Project) & Depleted Argon (Aria Project)
- **γ** : SiPM & ultra-clean Titanium

Further Depletion of Ar

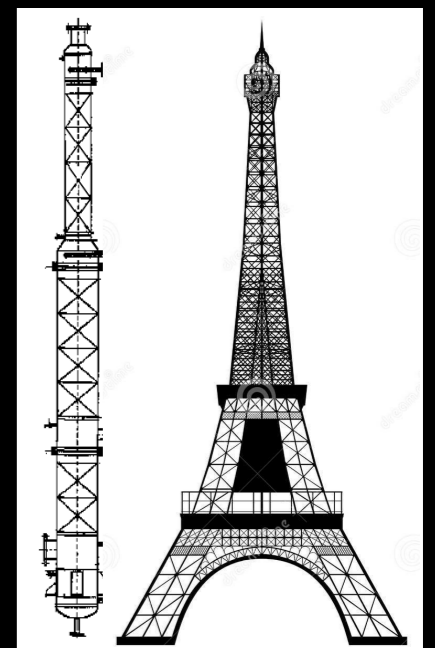
Urania (Underground Argon):

- Expansion of the argon extraction plant in Cortez, CO, to reach capacity of **100 kg/day** of Underground Argon



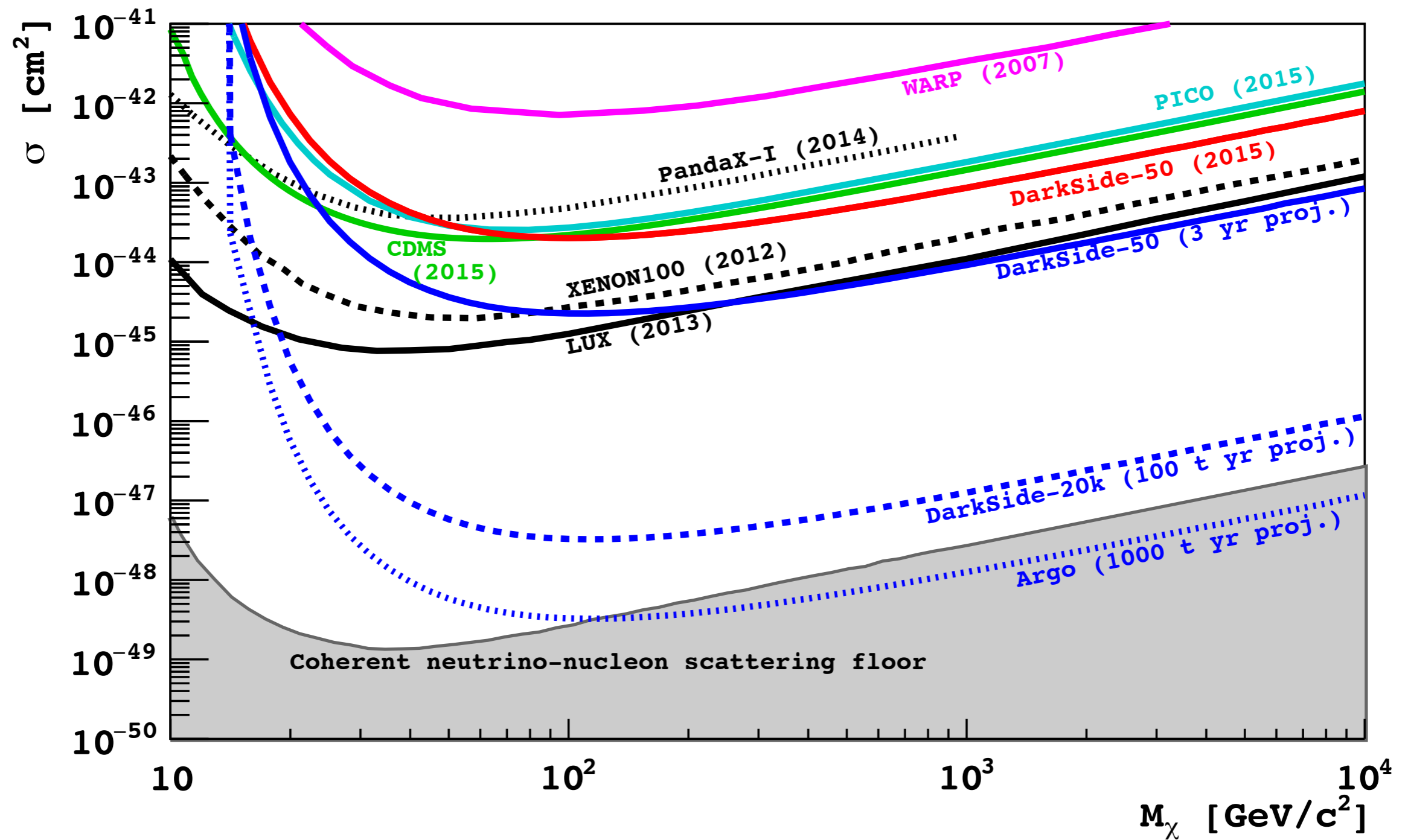
Aria (UAr Purification):

- Very tall column in the Seruci mine in Sardinia, Italy, for high-volume chemical and isotopic purification of Underground Argon



Experiment	σ [cm ²] @1 TeV/c ²	σ [cm ²] @10 TeV/c ²
LUX [10k kg×day Xe]	1.1×10^{-44}	1.2×10^{-43}
XENON [7.6k kg×day Xe]	1.9×10^{-44}	1.9×10^{-43}
DS-50 [1.4k kg×day Ar]	2.3×10^{-43}	2.1×10^{-42}
ArDM [1.5 tonne×yr Ar]	8×10^{-45}	7×10^{-44}
DEAP-3600 [3.0 tonne×yr Ar]	5×10^{-46}	5×10^{-45}
XENON-1ton [2.7 tonne×yr Xe]	3×10^{-46}	3×10^{-45}
LZ [15 tonne×yr Xe]	5×10^{-47}	5×10^{-46}
DS-20k [100 tonne×yr]	9×10^{-48}	9×10^{-47}
1 Neutrino Event [400 tonne×yr Ar or 300 tonne×yr Xe]	2×10^{-48}	2×10^{-47}
ARGO [1,000 tonne×yr]	9×10^{-49}	9×10^{-48}

Expected sensitivity



DarkSide-20k and Argo Lol Signatories

D. Franco, A Tonazzo - [APC Paris](#)
D. Alton - [Augustana College](#)
A. Kubankin - [Belgorod National Research University](#)
K. Keeter, B. Mount - [Black Hills State University](#)
L. Romero, R. Santorelli - [CIEMAT](#)
S. Horikawa, K. Nikolics, C. Regenfus,
A. Rubbia - [ETH Zürich](#)
S. Pordes - [Fermilab](#)
A. Gola, C. Piemonte - [FBK & TIFPA](#)
S. Davini - [GSSI](#)
E. Hungerford, A. Renshaw - [University of Houston](#)
M. Guan, J. Liu, Y. Ma, C. Yang, W. Zhong - [IHEP Beijing](#)
N. Canci, F. Gabriele, G. Bonfini, A. Razeto, N. Rossi,
F. Villante - [LNGS](#)
C. Jollet, A. Meregaglia - [IPHC Strasbourg](#)
M. Misziazek, M. Woicik, G. Zuzel - [Jagiellonian University](#)
K. Fomenko, A. Sotnikov, O. Smirnov - [JINR](#)
M. Skorokhvatov - [Kurchatov Institute Moscow](#)
A. Derbin, V. Muratova, D. Semenov,
E. Unzhakov - [PNPI Saint Peterburg](#)
S. De Cecco, C. Giganti - [LPNHE Paris](#)
H. O. Back - [PNNL](#)
M. Ghioni, A. Gulinatti, L. Pellegrini, I. Rech, A. Tosi,

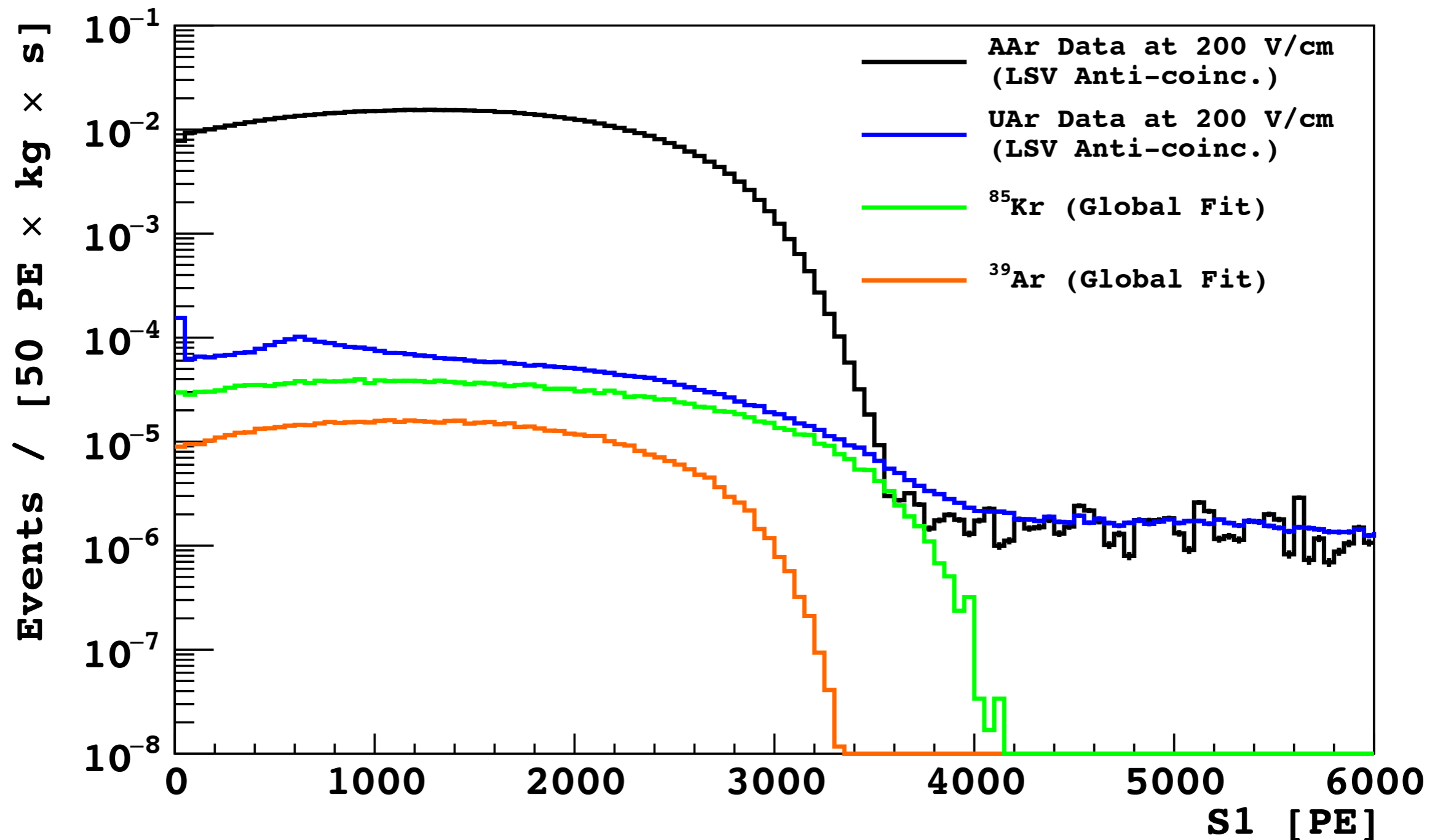
F. Zappa - [Politecnico di Milano](#)
C. Galbiati, A. Goretti, A. Ianni, P. Meyers,
M. Wada - [Princeton University](#)
A. Chepurnov, G. Girenok, I. Gribov, M. Gromov,
I. Zilcov - [SINP MSU Moscow](#)
C.J. Martoff, J. Napolitano, J. Wilhelmi - [Temple University](#)
E. Pantic - [UCDavis](#)
Y. Suvorov, H. Wang - [UCLA](#)
A. Pocar - [UMass Amherst](#)
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A. Devoto, M. Lissia, M. Mascia,
S. Palmas - [Università & INFN Cagliari](#)
M. Pallavicini, G. Testera,
S. Zavatarelli - [Università & INFN Genova](#)
D. D'Angelo, G. Ranucci - [Università & INFN Milano](#)
F. Ortica, A. Romani - [Università & INFN Perugia](#)
S. Catalanotti, A. Cocco, G. Covone, G. Fiorillo,
B. Rossi - [Università Federico II & INFN Napoli](#)
C. Dionisi, S. Giagu, M. Rescigno - [Università La Sapienza & INFN Roma](#)
S. Bussino, S. Mari - [Università & INFN Roma 3](#)
J. Maricic, R. Milincic, B. Reinhold - [University of Hawaii](#)
P. Cavalcante - [Virginia Tech](#)

Summary

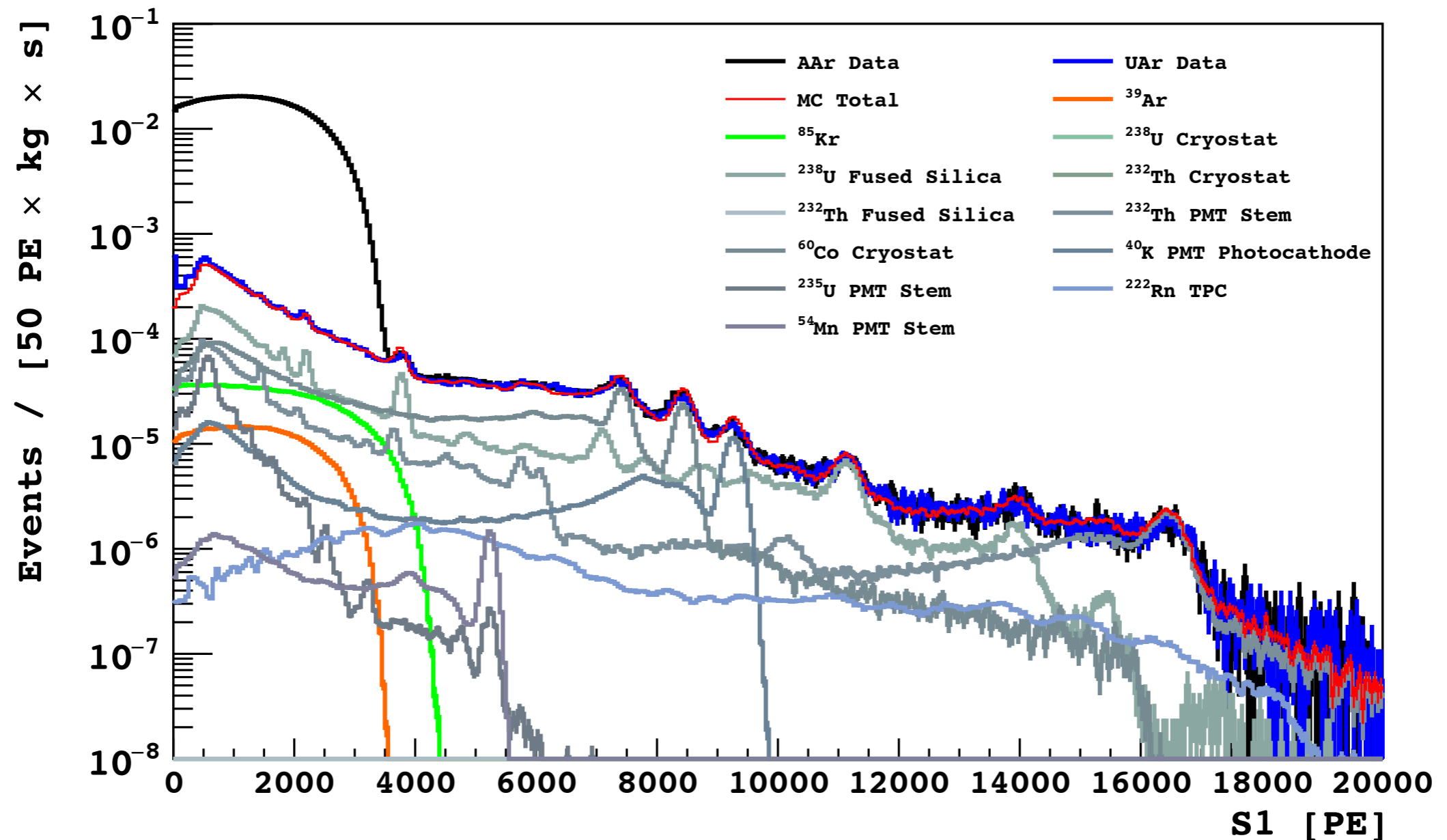
- **Background free**
 ^{39}Ar BG from **47.1 live days** (1422 kg · day fiducial) of AAr corresponds to that expected in **38.7 years of UAr** DS-50 run (>>planning physics run time, 3 years).
- Concentration of ^{39}Ar in **UAr** is **1400** times lower than in **AAr**.
- With the BG-free exposure of 1422 kg · day fiducial and depletion factor of 1400, DarkSide demonstrates **^{39}Ar BG** rejection at level of **5.5 tonne·year** with UAr.
- Future detectors are planned and Letter of Intent was submitted to LNGS April 27 2015. Proposal is under submission to NSF and INFN.

THE END

UAr First results (Field On)

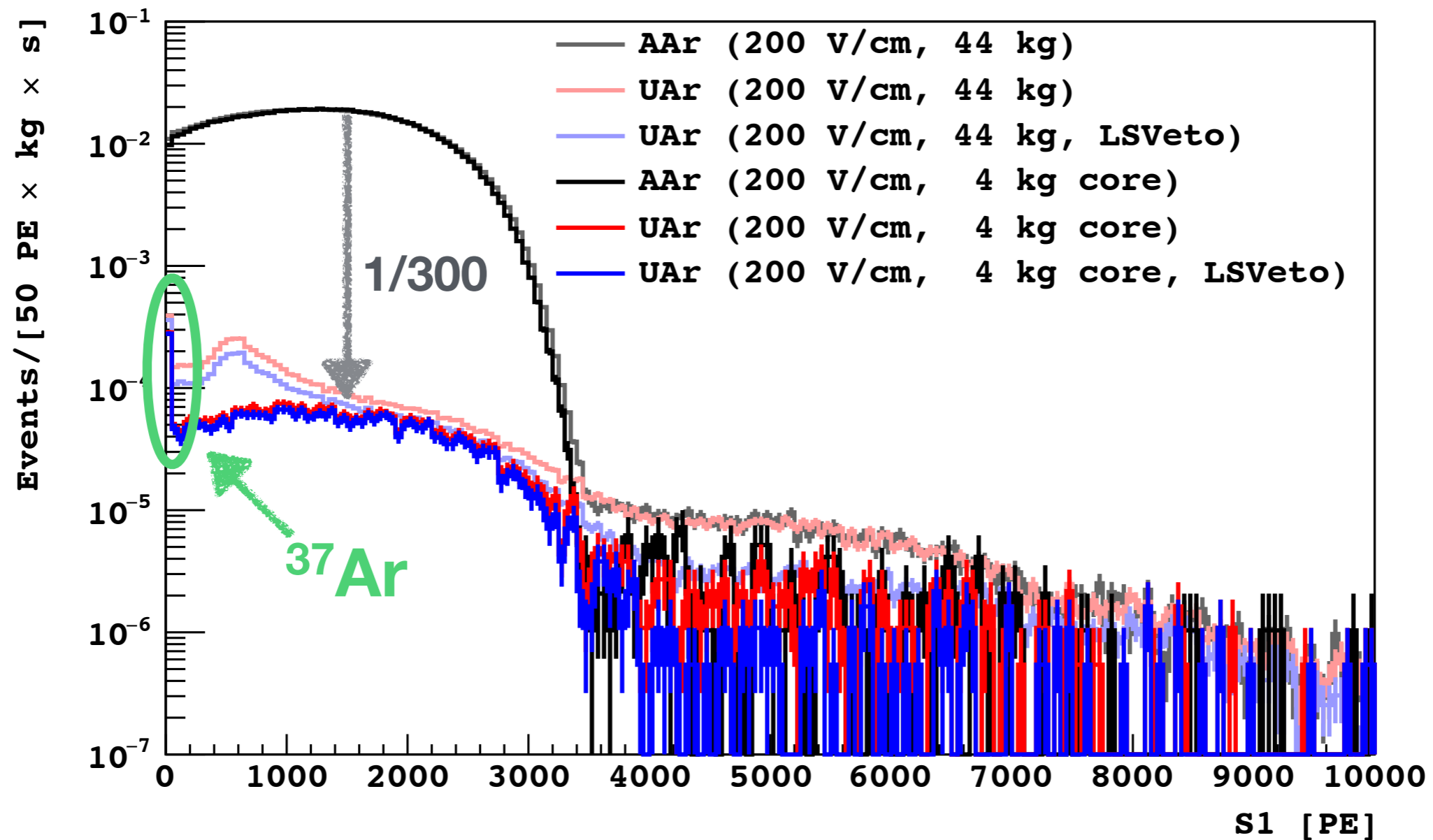


UAr cocktail fit



The radioactivities from fit match with expected activities.

^{37}Ar

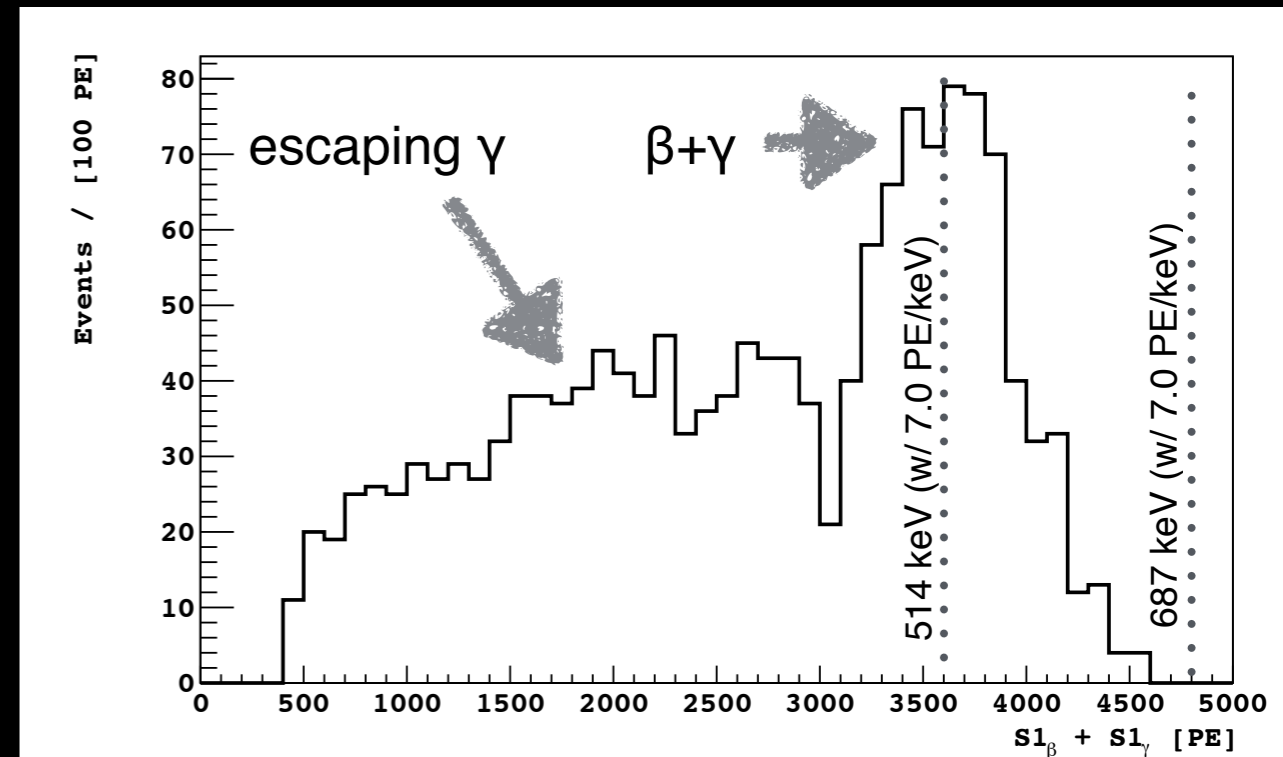
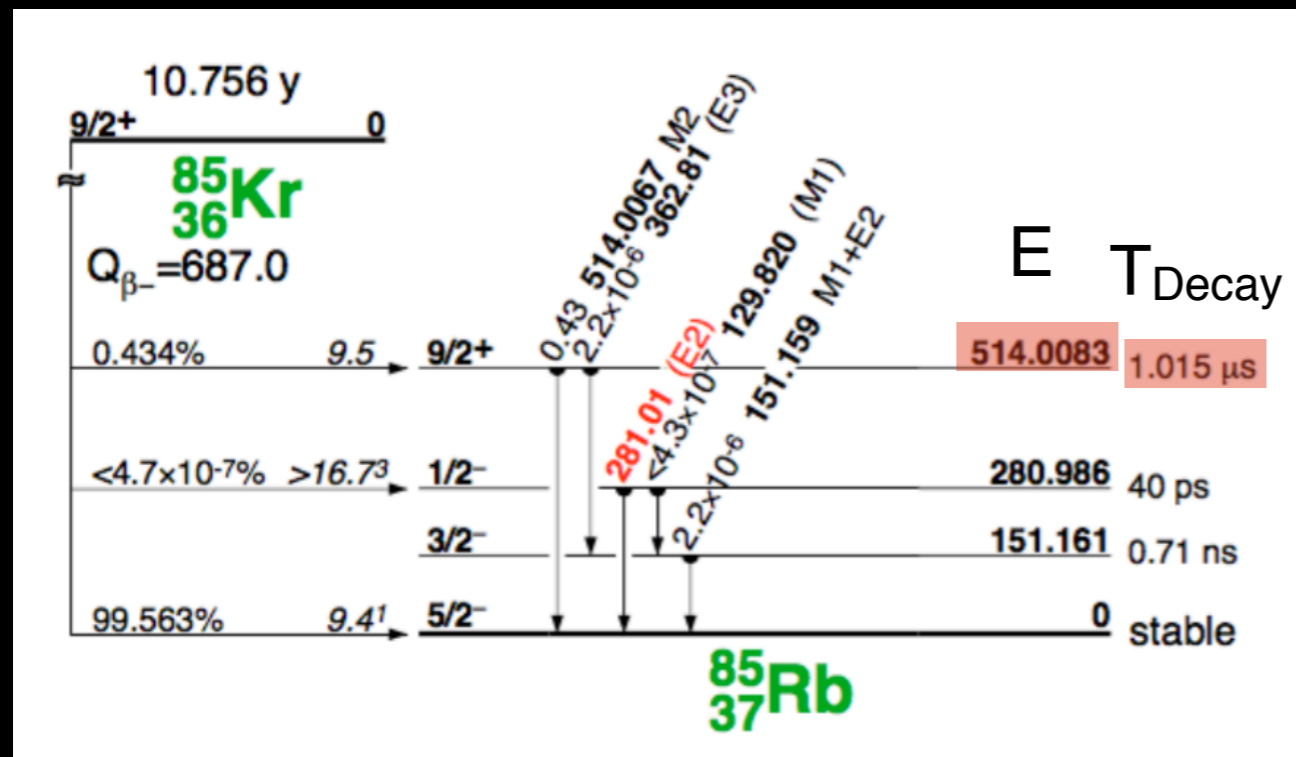


^{37}Ar is activated by cosmic rays.

Only 35 day half life

Provide low energy (~2-3 keV) calibration point.

^{85}Kr Contamination



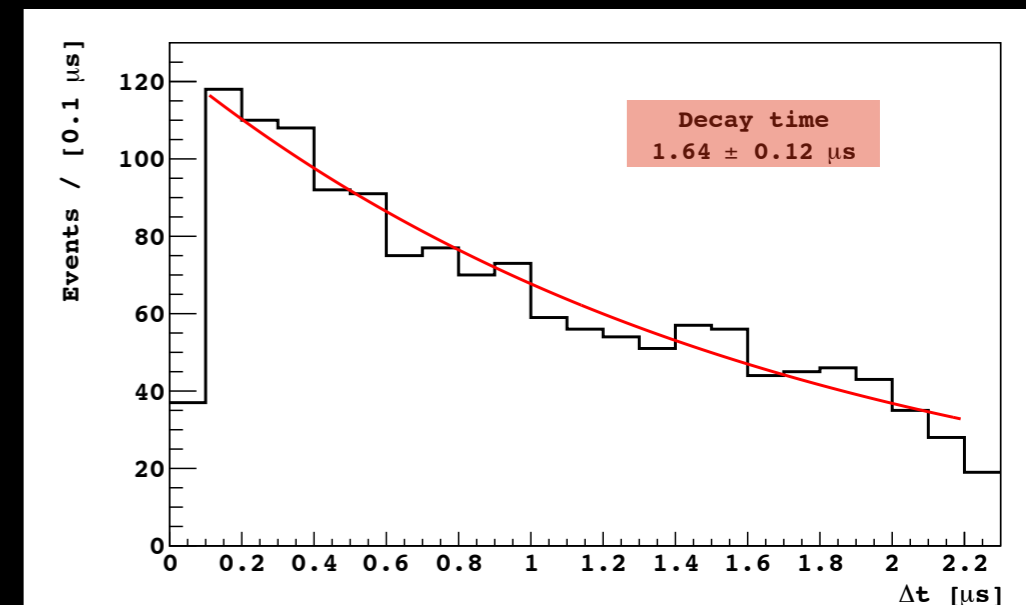
99.57% decay via β (678 keV)

0.43% decay via β (173 keV) + delayed γ (514 keV)
Measured meantime 1.64 μs in DS-50

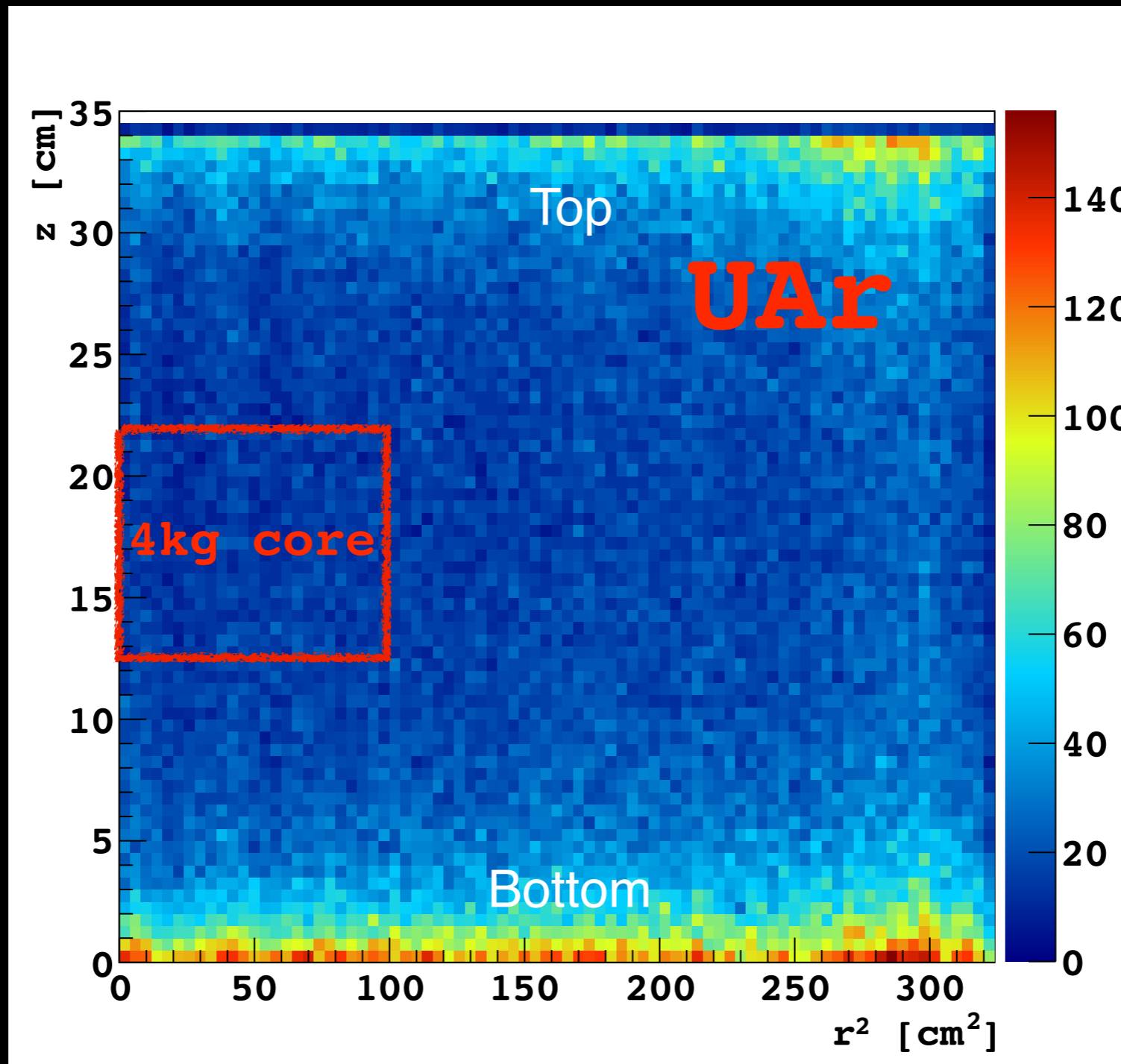
Rate in two branches (BR corrected)

35.3 ± 2.2 cpd

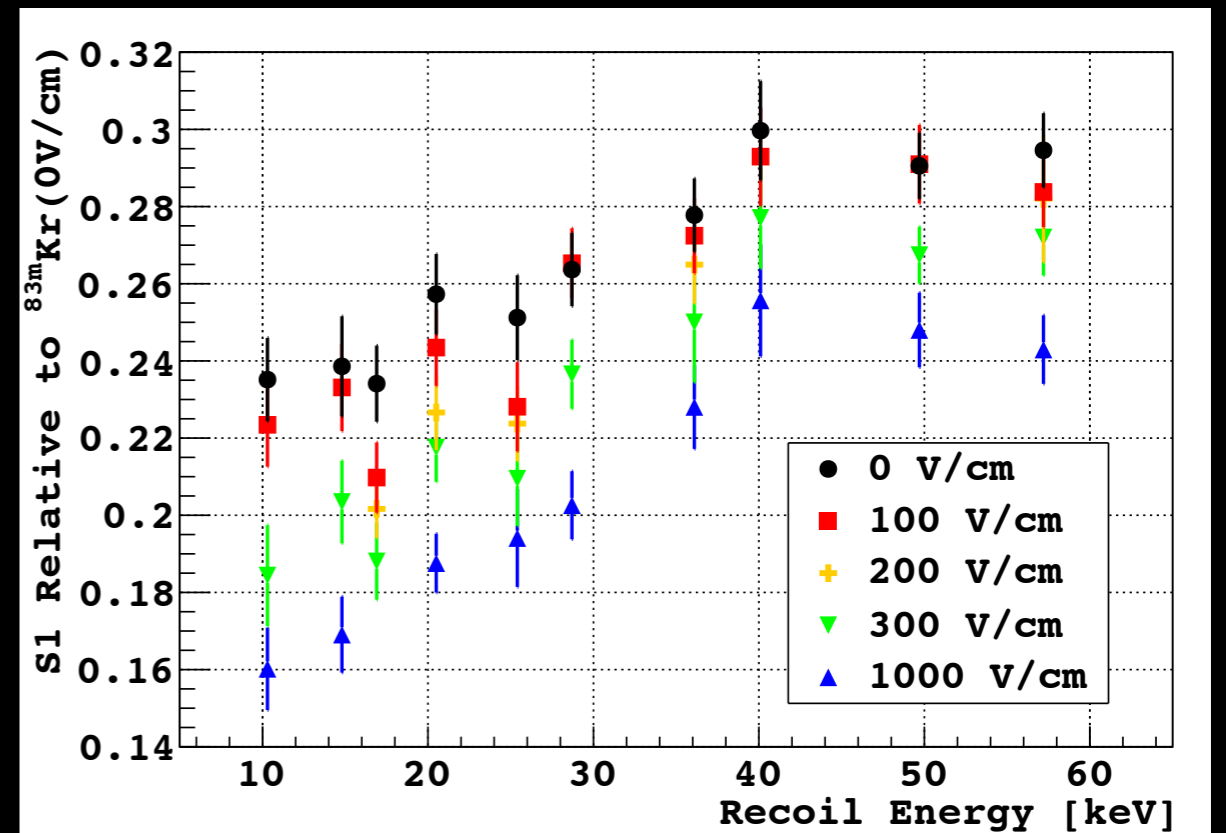
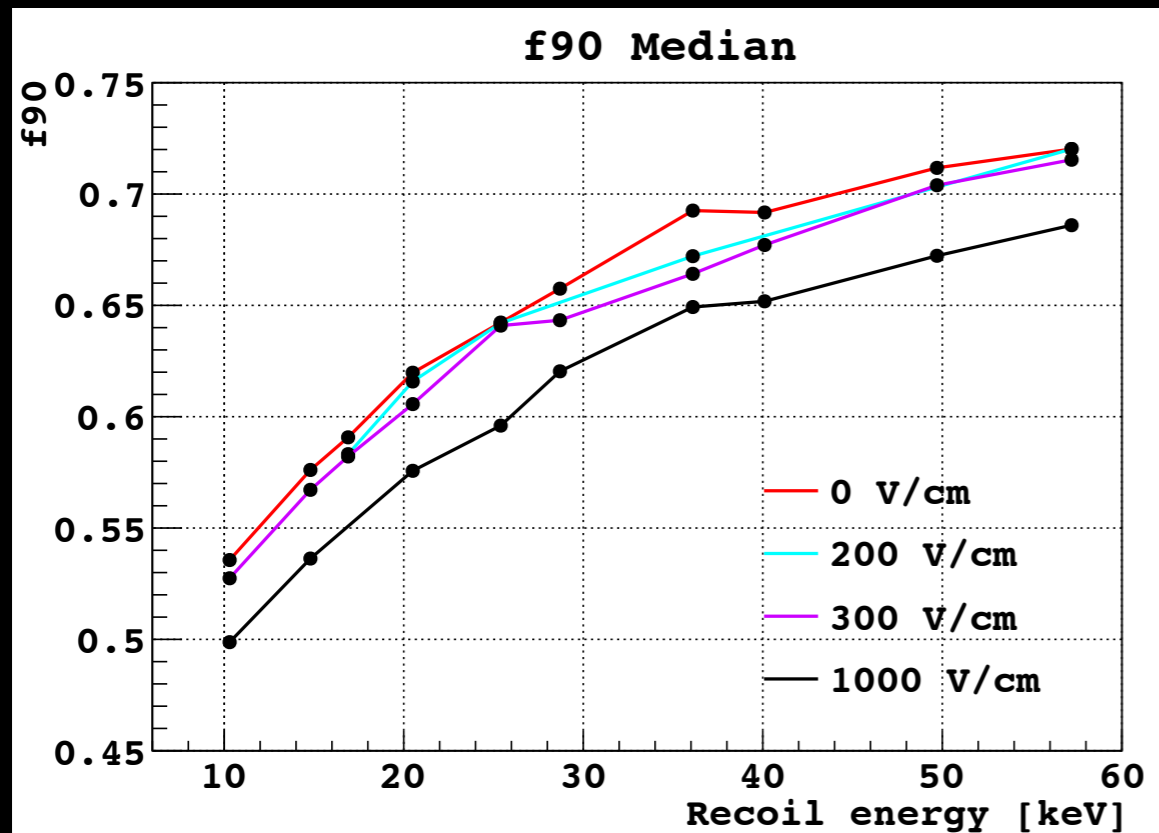
33.1 ± 0.9 cpd



Event Position in TPC



Data from SCENE and the plots

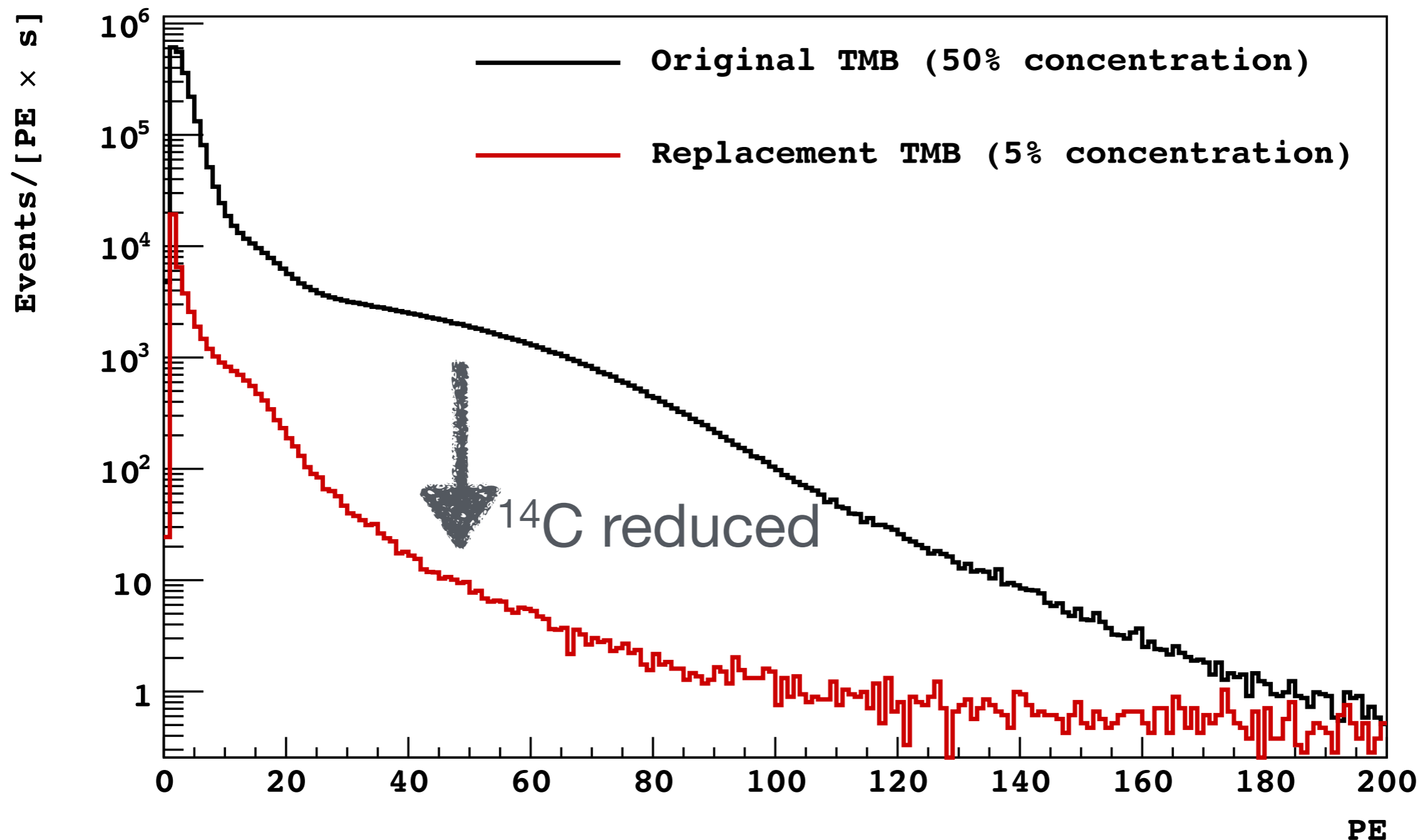


- Left : the median of the f90 distribution for nuclear recoils as a function of energy as measured in the SCENE experiment
- Right: the quenching factor for nuclear recoils as measured by the SCENE experiment

Kr calibration data is used for cross calibration of light yield between DS50 and SCENE.

SCENE (Phys. Rev. D 88, 092006 (2013), [arXiv:1406.4825](https://arxiv.org/abs/1406.4825))

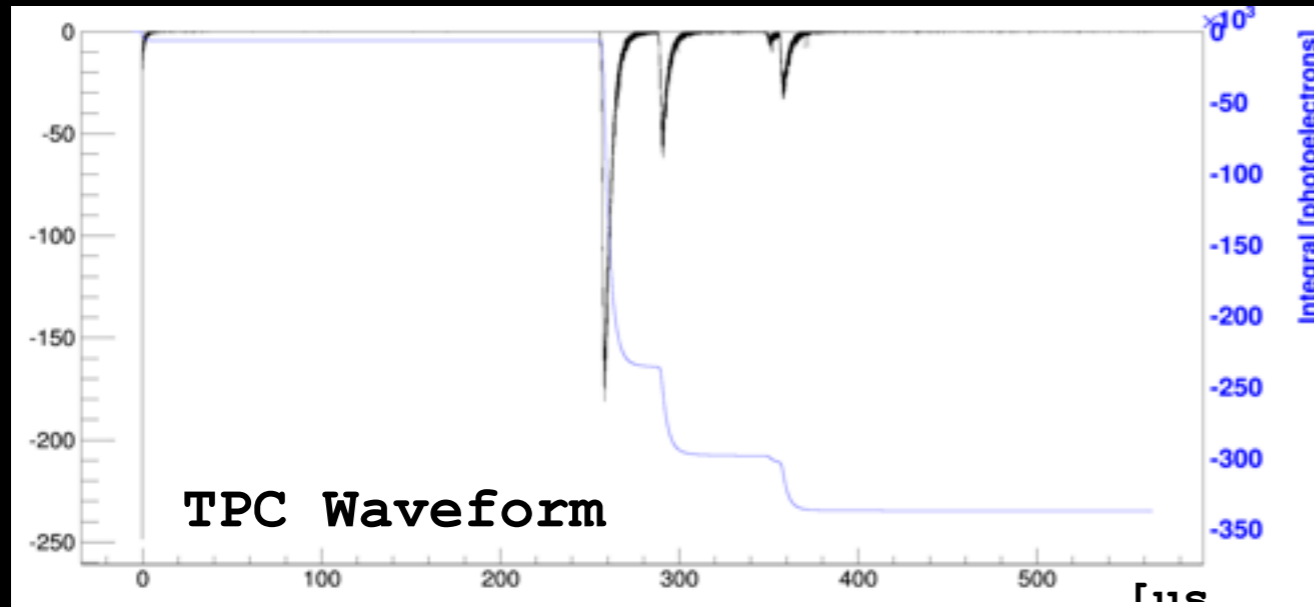
Status of Liquid Scintillator Veto



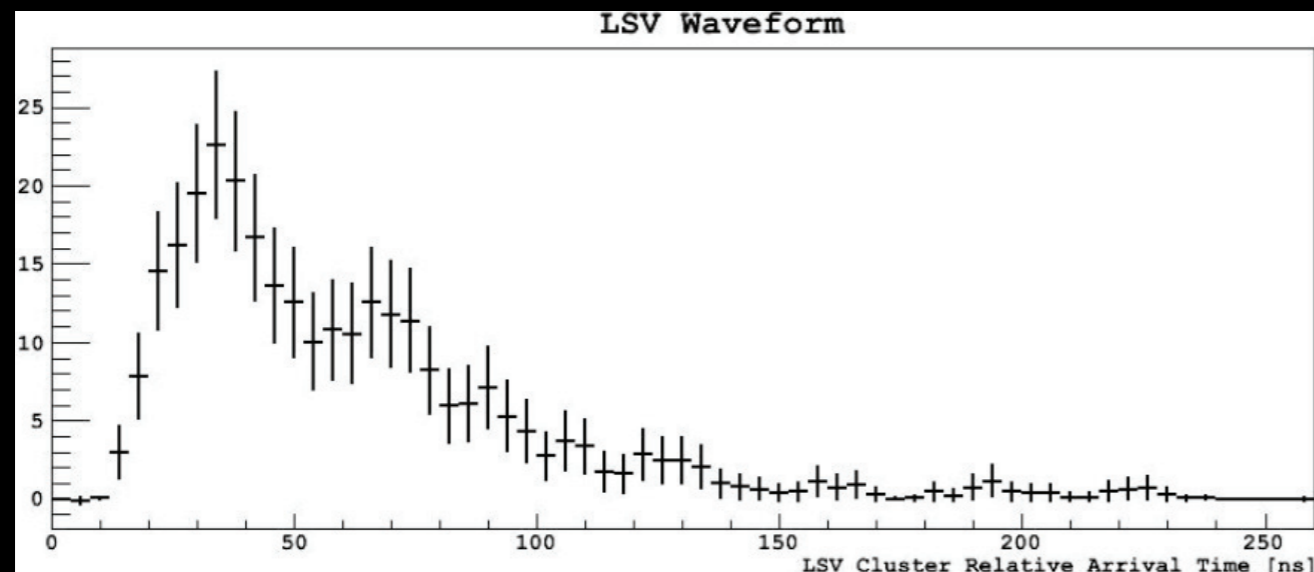
¹⁴C activity decreased from 150 kBq to 0.3 kBq.

Neutron Veto Commissioning

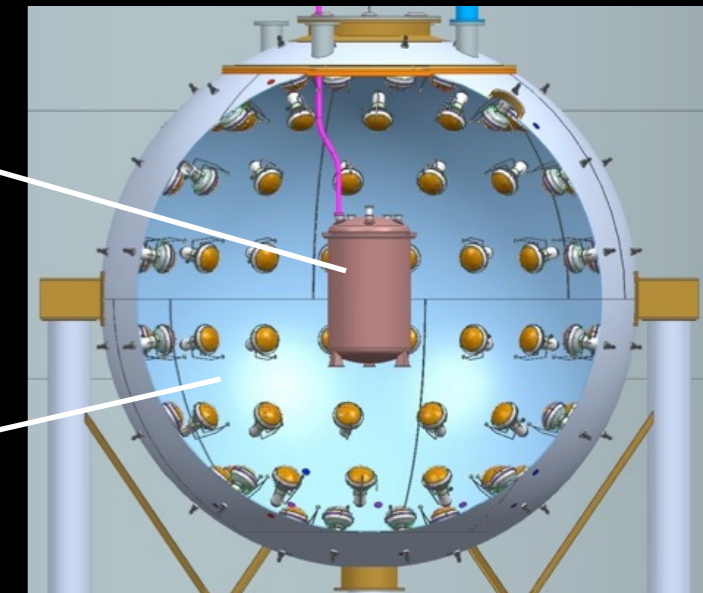
Coincident event in TPC and Neutron Veto



Electron recoil event with multiple S2 signals in TPC



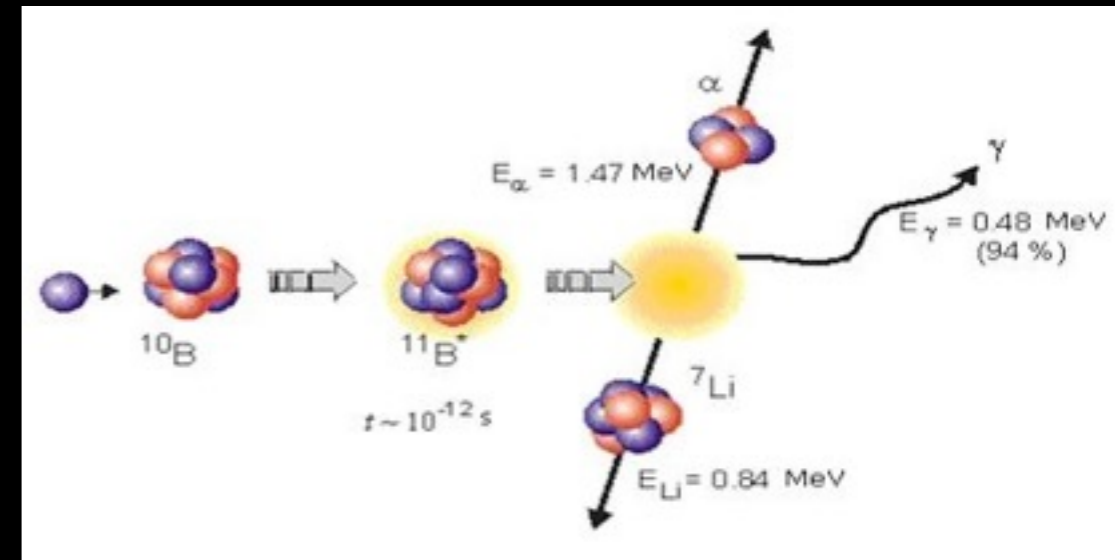
Coincident signal in liquid scintillator veto



Light Yield: liquid scintillator VETO LY of about 0.5 PE/keV_{ee}, satisfactory for VETO requirements.

Borated Liquid Scintillator

- High neutron capture cross section on boron allows for compact veto size
- Capture results in 1.47 MeV α particle - detected with high efficiency
- Short capture time ($2.3 \mu\text{s}$) reduces dead time loss



	Veto Efficiency (MC)
Radiogenic Neutrons	$> 99\%^*$
Cosmogenic Neutrons	$> 95\%$

Nuclear Instruments and Methods A 644, 18 (2011)

DarkSide-20k

20-tonnes fiducial dark matter detector
start of operations at LNGS within 2020
100 tonnextyear background-free search for dark matter

20–	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
DS–20k																				
ARGO																				

Argo

300-tonnes depleted argon detector
start of operations at LNGS within 2025
1,000 tonnextyear background-free search for dark matter
precision measurement of solar neutrinos